Subcontractor Report

July 2003 • NREL/SR-540-33957

Next Generation Natural Gas Vehicle Program Phase I: Clean Air Partners 0.5 g/hp-h NO_x Engine Concept

Final Report

H.C. Wong
Clean Air Partners, Inc.
San Diego, California

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

July 2003 • NREL/SR-540-33957

Next Generation Natural Gas Vehicle Program Phase I: Clean Air Partners 0.5 g/hp-h NO_x Engine Concept

Final Report

H.C. Wong
Clean Air Partners, Inc.
San Diego, California

NREL Technical Monitor: M. Frailey

Prepared under Subcontract No. NDX-1-31070-01

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Table of Contents

List of Figures and Tables ii
List of Acronyms and Abbreviations iii
1.0 Executive Summary 1
2.0 Introduction 3
3.0 Objectives 3
4.0 Technical Approach 4
5.0 Engine Hardware and Test Set-Up 6
5.1 Test Engine 6
5.2 Test Cell Set-Up and Instrumentation 6
5.3 Emission Reduction Module 7
5.3.1 PACCOLD-EGR System 7
5.3.2 ACCOLD-EGR System 7
5.4 Test Program and Procedure 7
6.0 Test Results 8
6.1 Baseline Configuration 8
6.2 PACCOLD-EGR Evaluation 9
6.2.1 ESC Mode 2 (1291 rpm, 100% load) 9
6.2.2 ESC Mode 6 (1291 rpm, 75% load) 10
6.2.3 ESC Mode 5 (1291 rpm, 50% load) 12
6.2.4 ESC Mode 7 (1291 rpm, 25% load) 14
6.2.5 ESC Mode 8 (1561 rpm, 100% load) 15
6.2.6 ESC Mode 4 (1561 rpm, 75% load) 17
6.2.7 ESC Mode 3 (1561 rpm, 50% load) 19
6.2.8 ESC Mode 9 (1561 rpm, 25% load) 20
6.2.9 ESC Mode 10 (1830 rpm, 100% load) 22
6.2.10 ESC Mode 12 (1830 rpm, 75% load) 23
6.2.11 ESC Mode 13 (1830 rpm, 50% load) 25
6.2.12 ESC Mode 11 (1830 rpm, 25% load) 27
6.3 Discussion 28
6.3.1 Exhaust Gas Recirculation 29
6.3.2 PACCOLD-EGR 30
6.3.3 Catalytic Particulate Filter 30
6.4 PACCOLD-EGR Demonstration 31
6.5 ACCOLD-EGR 32
7.0 Application and Feasibility of PACCOLD-EGR 33
7.1 Catalytic Particulate Filter 33
7.2 EGR Components 34
8.0 Summary and Conclusions 34
9.0 References 35
Appendix 1: Model Year 2002 C-12 Dual-Fuel Engine, Baseline ESC 13-Mode Test Results 36
Appendix 2: Model Year 2002 C-12 Dual-Fuel Engine Equipped with PACCOLD-EGR, ESC 13-Mode Test Results 38

List of Figures and Tables

Figure 1: PACCOLD-EGR Schematic 5
Figure 2: ACCOLD-EGR Schematic 5
Figure 3: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 2 9
Figure 4: Effect of Diesel Timing on HC-NO_x Tradeoff, ESC Mode 2 10
Figure 5: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 6 10
Figure 6: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 6 11
Figure 7: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 6 12
Figure 8: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 5 12
Figure 9: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 5 13
Figure 10: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 5 13
Figure 11: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 7 14
Figure 12: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 7 14
Figure 13: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 7 15
Figure 14: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 8 16
Figure 15: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 8 16
Figure 16: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 8 17
Figure 17: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 4 18
Figure 18: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 4 18
Figure 19: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 4 19
Figure 20: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 3 19
Figure 21: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 3 20
Figure 22: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 3 20
Figure 23: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 9 21
Figure 24: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 9 21
Figure 25: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 9 22
Figure 26: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 10 22
Figure 27: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 10 23
Figure 28: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 10 23
Figure 29: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 12 24
Figure 30: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 12 24
Figure 31: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 12 25
Figure 32: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 13 26
Figure 33: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 13 26
Figure 34: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 13 27
Figure 35: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 11 27
Figure 36: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 11 28
Figure 37: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 11 28
Figure 38: Effect of EGR Fraction on NO_x Emissions, ESC Mode 10 29
Figure 39: Effect of Lambda and EGR on Start of Combustion, ESC Mode 8 30
Figure 40: Schematic of Catalyzed Ceramic Particulate Filter 31

Table 1: C-12 Dual-Fuel Engine Specifications 6
Table 2: C-12 Dual-Fuel Engine ESC 13-Mode Cycle 8
Table 3: PACCOLD-EGR Performance 32

List of Acronyms and Abbreviations

ACCOLD	Active Clean and Cold
ACT	Air Charge Temperature
APBF-DEC	Advanced Petroleum-Based Fuels–Diesel Emissions Control
ATDC	After Top Dead Center
BSEC	Brake Specific Energy Consumption
BSHC	Brake Specific Hydrocarbons
$BSNO_x$	Brake Specific Nitrogen Oxides
CA	Crank Angle
CAP	Clean Air Partners, Inc.
CARB	California Air Resources Board
CDPF	Catalyzed Diesel Particulate Filter
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPF	Catalytic Particulate Filter
CRT	Continuously Regenerating Technology
DOE	U.S. Department of Energy
DECSE	Diesel Emissions Control–Sulfur Effects
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act
ESC	European Stationary Cycle
FTP	Federal Test Procedure
HC	Hydrocarbons
HC-SCR	Hydrocarbon-Based Selective Catalytic Reduction
HD	Heavy Duty
HPL	High-Pressure Loop
LNG	Liquefied Natural Gas
LNC	Lean-NO_x Catalyst
LPL	Low-Pressure Loop
NGNGV	Next Generation Natural Gas Vehicle
NGV	Natural Gas Vehicle
NMHC	Non-Methane Hydrocarbons
NO_x	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
PACCOLD	Passive Clean and Cold
PM	Particulate Matter
ppm	Parts per Million
ppmC	Parts per Million Carbon
TAB	Turbo Air Bypass
THC	Total Hydrocarbon
Urea-SCR	Urea-Based Selective Catalytic Reduction

1.0 Executive Summary

Natural gas is an abundant domestic fuel. The U.S. Department of Energy (DOE) supports natural gas vehicle (NGV) research and development to help the United States reach its goal of reducing dependence on imported petroleum, as outlined in the Energy Policy Act of 1992. Another benefit of NGVs is that they can reduce emissions of regulated pollutants compared with diesel vehicles.

This report details work conducted under the project titled “Assessment and Demonstration of the Clean Air Partners’ 12.0 L, 0.2 g/hp-h NO_x, 0.01 g/hp-h PM Natural Gas Engine for the Next Generation Natural Gas Vehicle Program.” This project was sponsored by DOE through the National Renewable Energy Laboratory (NREL) under Subcontract No. NDX-1-31070-01.

The objective of this project was to develop and demonstrate the prototype engine and vehicle technologies capable of reduced exhaust emissions and competitive operating costs for heavy-duty liquefied natural gas (LNG) vehicle application. Specific technical targets for Clean Air Partners (CAP) with the Caterpillar® C-12 Dual-Fuel™ engine include:

1. Nitrogen oxides (NO_x) emissions below 0.2 g/hp-h
2. Particulate matter (PM) emissions below 0.01 g/hp-h
3. Maintain efficiency of Caterpillar C-12 Dual-Fuel engine

CAP Dual-Fuel engines have been certified to California Low-NO_x emission levels since 1997. The emission reduction techniques used are essentially the same for all three sizes of Dual-Fuel engines (7, 10, and 12 L). The C-12 Dual-Fuel engine equipped with further improved, state-of-the-art combustion and aftertreatment equipment and strategies was demonstrated.

CAP’s emissions reduction module uses a regenerating diesel particulate filter (DPF) to remove solid and liquid particulates, enabling injection of clean and cold exhaust gas recirculation (EGR). Two emissions reduction modules were proposed: passive clean and cold (PACCOLD) EGR and active clean and cold (ACCOLD) EGR. The PACCOLD-EGR system combines DPF and EGR technologies. The catalyzed DPF was selected for the PACCOLD-EGR system after careful review of the available DPF technologies. The ACCOLD-EGR system consists of a lean-NO_x catalyst (LNC) in addition to the PACCOLD-EGR for further reduction of NO_x emissions. The ACCOLD-EGR system includes a controlled active addition of hydrocarbon fuel directly to the catalytic converter.

This project employed a step-by-step strategy and procedure for emissions reduction. CAP expected that NO_x emissions would be reduced to 0.5 g/hp-h with the PACCOLD-EGR system and 0.2 g/hp-h with the ACCOLD-EGR system. PM emissions would be below 0.01 g/hp-h with the use of a catalyzed DPF.

This report documents system design, fabrication, and experiments conducted on the PACCOLD-EGR system. The following emissions and fuel consumption results have been demonstrated with the PACCOLD-EGR system over the European Stationary Cycle (ESC):

Non-methane hydrocarbons (NMHC):	1.44 g/hp-h
Carbon monoxide (CO):	0.05 g/hp-h
NO_x:	0.54 g/hp-h
PM:	0.0037 g/hp-h
Brake specific energy consumption (BSEC):	7,610 Btu/hp-h

In addition, the following conclusions about the PACCOLD-EGR system were reached:

- A reduction in NO_x of about 4% for 1% of EGR mass fraction is suggested as a working guideline.
- EGR mass fraction and pilot injection timing are the dominant parameters affecting NO_x emissions.
- Unfavorable HC tradeoff for NO_x is evident with retarded pilot injection timing.
- A total hydrocarbons catalyst will be required to further reduce NMHC and methane emissions.

Successful implementation of the PACCOLD-EGR technology will rely on the product development of catalytic particulate filter (CPF) and EGR components. The California Air Resources Board (CARB) verified CAP's CPF, manufactured by Engelhard, for use with a specified list of natural gas/diesel Dual-Fuel engines in August 2002. This verification applies to specific CAP Dual-Fuel engines and to Caterpillar engines that have been converted to Dual-Fuel operation using the CAP Dual-Fuel retrofit systems.

The EGR system has been proven to be an effective tool for helping passenger car and other light-duty vehicles meet emissions requirements. It represents a viable technology and an important contributor to meeting the 2004 U.S. Environmental Protection Agency (EPA) NO_x emission standards for heavy-duty truck engines. EGR technologies have progressed significantly in response to the pull-ahead of 2004 emission standards to October 1, 2002. To date, EGR technologies have been implemented on most of the heavy-duty on-highway diesel truck engines sold after October 1, 2002. The PACCOLD-EGR system will be implemented on CAP's Dual-Fuel engines once the CPF and EGR system components are validated.

In December 2002, CAP concluded that the ACCOLD-EGR system as proposed could not meet the objectives of the project. Tests were performed on LNC technology under the Diesel Emissions Control–Sulfur Effects (DECSE) Program, sponsored by DOE, NREL, Oak Ridge National Laboratory, the Engine Manufacturers Association, and the Manufacturers of Emission Controls Association. These tests showed that LNC technology is not attractive compared with other NO_x reduction technologies. CAP decided in January 2003 not to pursue the ACCOLD-EGR system under the Next Generation Natural Gas Vehicle (NGNGV) Program because of lack of support from the government and private sectors for further development of LNC technology.

This final technical summary was prepared and submitted to NREL in fulfillment of the contract, to document all of the findings from this project.

2.0 Introduction

Because of the nation's concern about energy security and air pollution, congress enacted the Clean Air Act Amendments of 1990 and the Energy Policy Act (EPAct) of 1992, which have forced broad changes in fuels and vehicles. Reformulated gasoline, clean diesel, and alternative fuels are receiving wide attention as industry works to comply with the acts. Many air quality non-attainment areas will need to increase alternative fuel use to meet air quality standards. Heavy-duty vehicles accounted for the largest increase in transportation-related U.S. petroleum consumption in the past 15 years. The U.S. Department of Energy (DOE) identified the development of a Next Generation Natural Gas Vehicle (NGNGV) as a strategic element in its program to reduce oil imports and vehicle pollutants. Natural gas, both compressed (CNG) and liquefied (LNG), is a clean-burning, abundant, domestically available fossil fuel that has emerged as an alternative fuel of choice within the truck and bus sectors.

DOE selected the National Renewable Energy Laboratory (NREL) to lead the effort to develop commercially viable medium- and heavy-duty natural gas vehicles (NGVs) to help non-attainment areas reduce pollutant emissions. The vision is to develop one new medium-duty (Class 3-6) CNG vehicle and one new heavy-duty (Class 7-8) LNG vehicle that will be available as early as 2004 but no later than 2007 to help non-attainment areas reduce criteria pollutants from vehicles. Medium- and heavy-duty NGVs are available today. This program aims to advance the technology and vehicles by commercially implementing DOE-supported advanced technologies, including advanced natural gas engines, new materials, enhanced natural gas fuel storage, and reduced aerodynamic drag. The program's goal is for these new vehicles to have nitrogen oxides (NO_x) emissions at or below 0.5 g/hp-h and particulate matter (PM) emissions at or below 0.01 g/hp-h, which represent a significant step-change in NGV technology. The most ambitious goal is that these next-generation vehicles should be fully competitive—technically and commercially viable—with their conventionally fueled counterparts.

Dual-Fuel™ natural gas engines retain the diesel compression ratio at over 16:1. The air and gas mixture is ignited by a small charge of diesel fuel that is injected directly into the cylinder. The Dual-Fuel engine provides the low-NO_x emissions of a spark-ignited, lean-burn natural gas engine with the high efficiency and power output of a diesel engine. The base Caterpillar® C-12 Dual-Fuel engine is rated at 410 hp and 1250 ft-lb of peak torque. It has been widely used as a prime mover on heavy (Class 8) LNG vehicles that meet California low-NO_x emission standards.

3.0 Objectives

The objective of this project is to assess and demonstrate the proposed technologies and methods for emissions reduction of an existing Caterpillar C-12 Dual-Fuel engine for heavy-duty LNG vehicle application. Specific technical targets include:

- NO_x emissions below 0.2 g/hp-h
- PM emissions below 0.01 g/hp-h
- Maintain efficiency of C-12 Dual-Fuel engine

This project was a comprehensive review, evaluation, and demonstration of Clean Air Partners' (CAP's) proposed passive clean and cold (PACCOLD) exhaust gas recirculation (EGR) and active clean and cold (ACCOLD) EGR technology. It included the following specific tasks:

- Overall project coordination
- Review of technical and economic viability of the PACCOLD-EGR incorporated onto the existing Caterpillar C-12 Dual-Fuel truck engine
- Design and fabrication of hardware
- Modification of current control software
- Evaluation of the effect of PACCOLD-EGR
- Demonstration of engine performance and emissions on C-12 Dual-Fuel engine equipped with PACCOLD-EGR
- Evaluation of the effect of ACCOLD-EGR
- Demonstration of engine performance and emissions on C-12 Dual-Fuel engine equipped with ACCOLD-EGR
- Review and establishment of specific technical information on the final design of the ACCOLD-EGR system

4.0 Technical Approach

PACCOLD

The use of a full-time particulate filter in the exhaust permits use of a greatly simplified EGR system by injecting cooled EGR directly into the turbo compressor inlet, now possible because the EGR has been filtered and is clean enough to enter the compressor and aftercooler without the risk of contamination. This low-pressure loop (LPL) EGR system uses exhaust gas that has been filtered. It preserves turbocharger performance by allowing all exhaust gas to be used in the turbine and requires less EGR cooling. Integrating the existing low-NO_x Dual-Fuel engine with a diesel particulate filter (DPF) and 20% EGR should achieve a NO_x level of 0.5 g/hp-h, assuming 4% NO_x reduction will be achieved with 1% of EGR. This approach is called "passive clean and cold" EGR because it does not use a reductant. The system is shown schematically in Figure 1.

ACCOLD

With the addition of a lean-NO_x catalyst (LNC) using diesel fuel as a reducing agent, it should be possible to attain further reduction in NO_x from 0.5 to 0.2 g/hp-h. This second approach is called "active clean and cold" EGR because there is a controlled active addition of fuel directly to the catalytic converter. This system is shown schematically in Figure 2.

The desired reaction in a LNC, which is also denoted as hydrocarbon-based selective catalytic reduction (HC-SCR), is shown in the unbalanced equation below:

$$HC + NO_X \rightarrow N_2 + CO_2 + H_2O$$

The main advantage of the LNC system with a CAP Dual-Fuel engine is that a reductant source is already on-board. Using the vehicle fuel as a reductant requires no vehicle changes noticeable to the driver and requires no additional infrastructure investments.

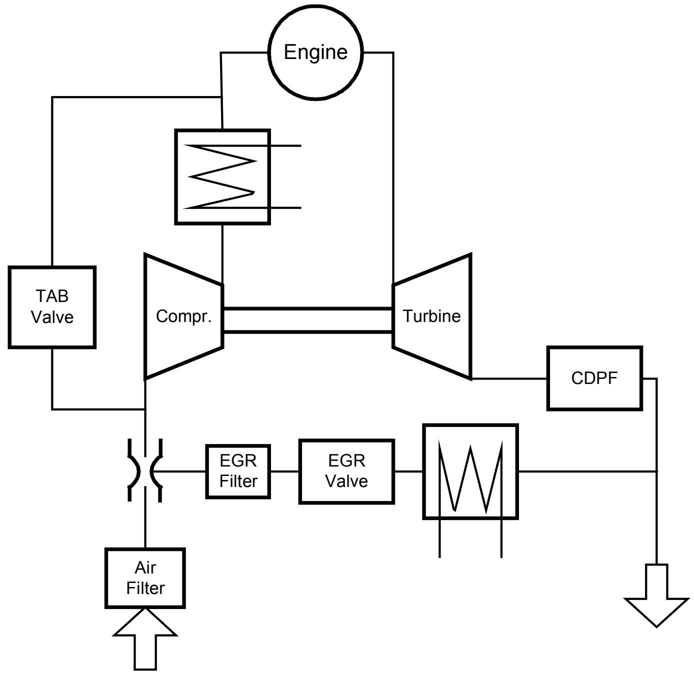


Figure 1: PACCOLD-EGR Schematic

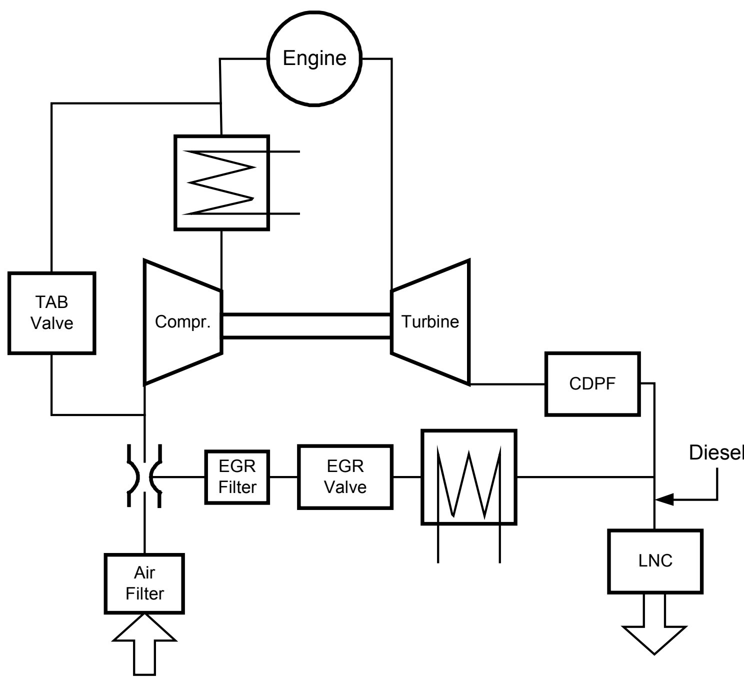


Figure 2: ACCOLD-EGR Schematic

System design and fabrication and experiments conducted on the above technologies are described in the following sections of this report.

5.0 Engine Hardware and Test Set-Up

5.1 Test Engine

The engine used for this project was a model year 2002 CAP C-12 Dual-Fuel engine with the specifications shown in Table 1.

Table 1: C-12 Dual-Fuel Engine Specifications

Number of Cylinders and Arrangement	6 in-line
Bore and Stroke	130 mm x 150 mm
Displacement	11.9 L
Compression Ratio	16.25:1
Rated Power and Speed	410 hp at 1800 rpm
Peak Torque and Speed	1250 ft-lb at 1200 rpm
Diesel Fuel System	Mechanically actuated electronic unit injector
Gaseous Fuel System	Multi-point sequentially-timed port injection

5.2 Test Cell Set-Up and Instrumentation

Engine tests were conducted in an instrumented test cell, specified below:

Dynamometer: General Electric model TH16M, Capacity 600-hp 1000/4000 rpm

Measurement:

Air Flow: Meriam Laminar Flow Element, 1000 SCFM nominal flow rate
Diesel Flow: KFlow model K20 flow meter, 0-2 lbs/min range
EG&G Turbine flow meter
Gas Flow: Micro Motion ELITE flow meter model CMF025, 16 lbs/min nominal flow rate
Temperature: K-type thermocouples
Pressure: Kavlico pressure transducers

Data Acquisition: National Instruments SXCI series, 32 channels analog input, 4 channels analog output

Emissions Equipment:

Horiba Mexa 7100D Emissions Bench

- CO_2 analyzer, 3% and 20% by volume ranges
- CO analyzer, 2500-ppm range

- O_2 analyzer, 25% by volume range
- THC analyzer, 500-ppmC and 5,000-ppmC ranges
- CH_4 analyzer, 4,000-ppmC and 25,000-ppmC ranges
- NO_x analyzer, 500-ppm and 2,500-ppm ranges

Horiba MDLT DLS-2300 Micro Dilution Tunnel

Charge Air Cooling: Thermal controlled air to water cooler

Cylinder pressure was measured by a Kistler piezoelectric pressure transducer placed into the cylinder head of cylinder number 6. The cylinder pressure and crank angle (CA) position signal from the optical encoder, with a resolution of 0.2 CA degrees, were input into the AVL 619 Indimeter for use in continuous engine monitoring and basic combustion measurements.

5.3 Emission Reduction Module

5.3.1 PACCOLD-EGR System

The system (Figure 1) consists of the following:

- Engelhard DPX catalyzed DPF
- EGR cooler, designed and fabricated by CAP
- Venturi assembly, designed and fabricated by CAP
- EGR filter

5.3.2 ACCOLD-EGR System

The system (Figure 2) consists of the Johnson Matthey LNCs in addition to the PACCOLD-EGR system. The LNCs consist of two catalysts in series, low temperature and high temperature, to broaden the operating temperature window.

5.4 Test Program and Procedure

Engine tests were designed to evaluate and the effect of PACCOLD-EGR and ACCOLD-EGR in conjunction with other existing control variables and strategies used on current C-12 Dual-Fuel engines. The complete engine test matrix is described below:

Test points: Engine was tested at 13 speed-load points as defined by the 13-mode European Stationary Cycle (ESC).

Test matrix: Test matrices were established for each individual test point with common targets, control factors, and constraints (described below).

Targets:

- 0.5 and 0.2 g/hp-h NO_x (PACCOLD and ACCOLD, respectively) and 0.01 g/hp-h PM emissions
- Same fuel economy as the current C-12 Dual-Fuel engine

Control factors:

- EGR rate, manually adjusted

- Gas lambda
- Pilot injection timing
- EGR temperature
- Air charge temperature (ACT)

Constraints:

- Audible knock
- Exhaust temperature
- ACT (mixture of air and recirculated exhaust gas)

6.0 Test Results

6.1 Baseline Configuration

An ESC 13-mode test was conducted on the current C-12 Dual-Fuel engine configuration as a baseline, before the PACCOLD-EGR system was installed. Table 2 shows the dynamometer operation of the C-12 Dual-Fuel test engine.

Table 2: C-12 Dual-Fuel Engine ESC 13-Mode Cycle

Mode No.	Engine Speed (rpm)	Percent Load	Weighting Factor	Mode Length (min)
1	700	Idle	0.15	4
2	1291	100	0.08	2
3	1561	50	0.10	2
4	1561	75	0.10	2
5	1291	50	0.05	2
6	1291	75	0.05	2
7	1291	25	0.05	2
8	1561	100	0.09	2
9	1561	25	0.10	2
10	1830	100	0.08	2
11	1830	25	0.05	2
12	1830	75	0.05	2
13	1830	50	0.05	2

The baseline ESC test had the following results:

Brake specific hydrocarbon (BSHC):	12.38 g/hp-h
Brake specific CO:	4.05 g/hp-h
Brake specific NO_x ($BSNO_x$)	2.38 g/hp-h
Brake specific energy consumption (BSEC):	7,124 Btu/hp-h
Gas Substitution:	79.97%

Appendix 1 details the baseline ESC 13-mode test results.

6.2 PACCOLD-EGR Evaluation

The effect of PACCOLD-EGR was evaluated in accordance with the test procedure described in Section 4.4. Parametric studies of the following parameters were performed at each mode of the ESC, except Mode 1 (idling at 700 rpm):

- EGR mass fraction
- Gas lambda
- Pilot injection timing

Test results were analyzed and presented to reflect the optimum emissions and fuel consumption and other performance tradeoffs at each mode. These are discussed in the following sections.

6.2.1 ESC Mode 2 (1291 rpm, 100% load)

The engine equipped with the PACCOLD-EGR system was tested at 1291 rpm and 100% load. The C-12 Dual-Fuel engine is operating with 100% diesel fuel at this mode. ACT was maintained at 38-42°C. EGR mass fraction was manually adjusted at 5%-16% and was calculated throughout this project from the measured EGR mass flow and fresh air mass flow as follows:

$$EGRMassFraction = \frac{EGRMassFlow}{EGRMassFlow + FreshAirMassFlow}$$

Figure 3 shows the tradeoff of BSHC for $BSNO_x$ at various EGR rates. It clearly shows the effect of EGR mass fraction on NO_x reduction. As the EGR rate increases, NO_x emissions decrease at a rate of more than 4% for every 1% of EGR mass fraction. No significant increase in hydrocarbons (HC) is observed because the Dual-Fuel engine is operating with 100% diesel fuel at this mode.

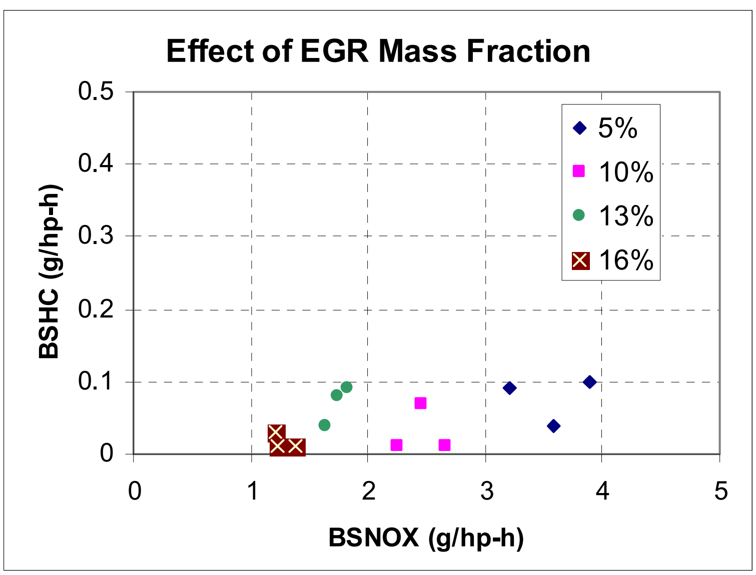


Figure 3: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 2

Diesel injection timing was also swung 2 degrees CA, advanced and retarded from nominal. Effect of diesel timing on the tradeoff of BSHC for $BSNO_x$ is shown in Figure 4. Figures 3 and 4 indicate that the EGR mass fraction is the dominant parameter affecting NO_x emissions compared with diesel timing.

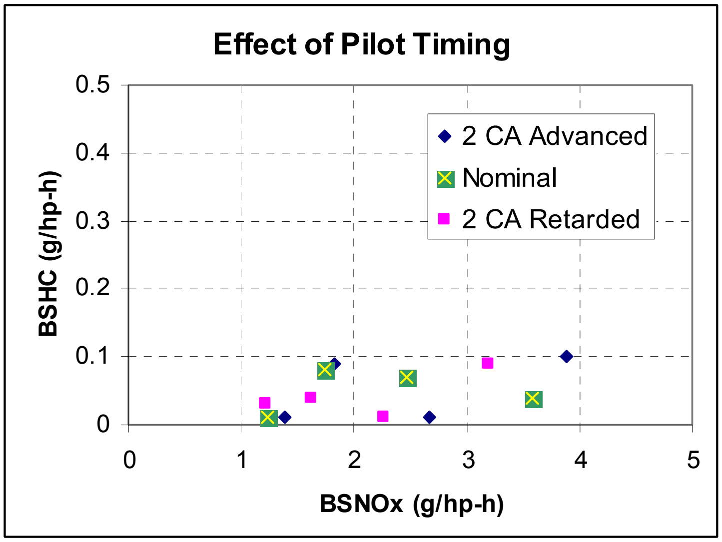


Figure 4: Effect of Diesel Timing on HC-NO_x Tradeoff, ESC Mode 2

6.2.2 ESC Mode 6 (1291 rpm, 75% load)

The Dual-Fuel engine equipped with PACCOLD-EGR system was tested at Mode 6 (1291 rpm and 75% load) with the same method as tested at Mode 2. ACT was maintained at 32-40°C. The EGR mass fraction was manually adjusted at 5%-15%. Figure 5 shows the tradeoff of BSHC for $BSNO_x$ at various EGR rates. It also suggests a similar reduction in NO_x of about 4% for 1% EGR mass fraction.

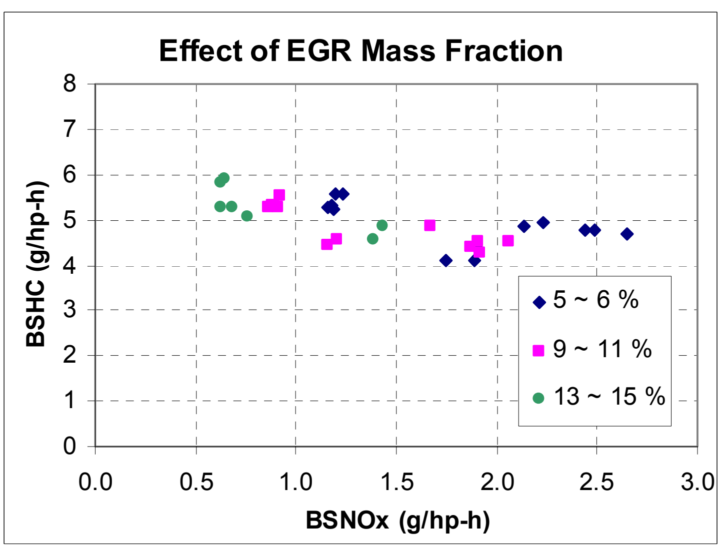


Figure 5: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 6

Excess air ratio is defined conventionally as the ratio of the actual mass of the available air and the stoichiometric air requirement for complete combustion. In the case of pilot-ignited natural gas engines, it is reasonable to assume that combustion of pilot fuel is completed prior to the combustion of natural gas. Therefore, λ_{gas} is calculated by the following equation:

$$\lambda_{gas} = \frac{AirFlow - 14.5 \times DieselFlow}{NaturalGasFlow \times 16.07}$$

The numbers 14.5 and 16.07 are the stoichiometric air/fuel ratios for pilot diesel fuel and natural gas, respectively.

With the introduction of EGR, the actual mass of the available air for combustion includes the unburned oxygen within the recirculated exhaust gas. λ_{gas} is therefore calculated with the corrected air mass flow and is denoted as "Corrected λ_{gas}" throughout this report.

The effect of Corrected λ_{gas} on the HC and NO_x tradeoff was also analyzed and is shown in Figure 6.

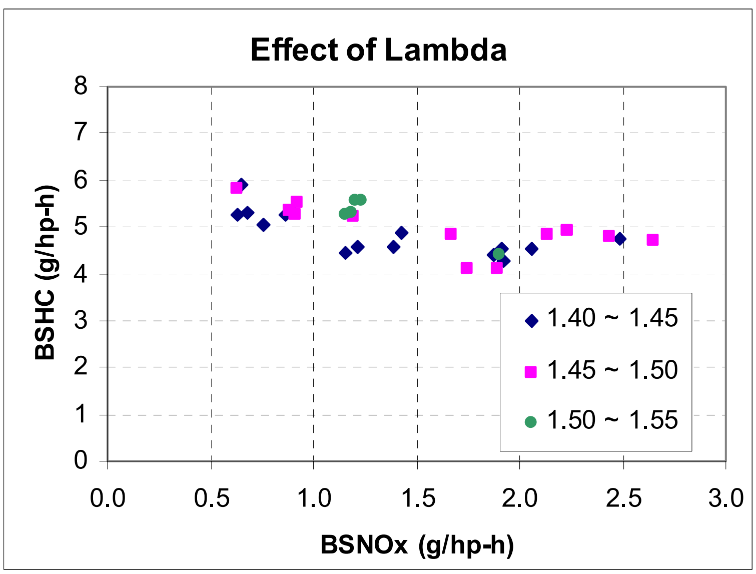


Figure 6: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 6

While EGR rate was modulated 5%-15%, pilot injection timing was swept from nominal to 2 degrees CA, advanced and retarded. Figure 7 demonstrates the effect of pilot injection timing on HC and NO_x tradeoff. Figures 5, 6, and 7 suggest that EGR mass fraction and pilot injection timing are the dominant parameters in NO_x reduction compared with Corrected λ_{gas}, in ESC Mode 6.

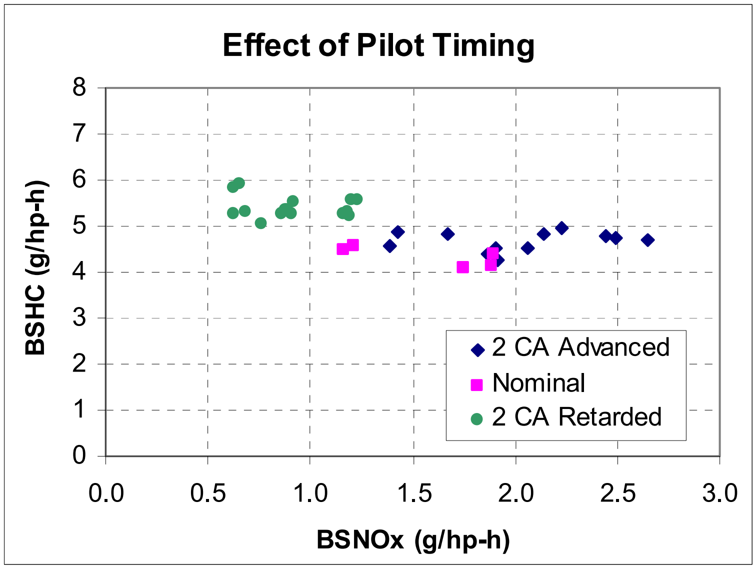


Figure 7: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 6

6.2.3 ESC Mode 5 (1291 rpm, 50% load)

The parametric study was performed at 1291 rpm and 50% load. ACT was maintained at 29-34^{o}C. While EGR mass fraction was manually adjusted at 5%-20%, the turbo air bypass (TAB) valve was modulated to vary the Corrected λ_{gas} at 1.6-1.9, and pilot injection timing was adjusted to +/- 2 degrees CA from nominal timing. Figures 8-10 show the effects of EGR rate, Corrected λ_{gas}, and pilot timing, on the HC and NO_x tradeoff.

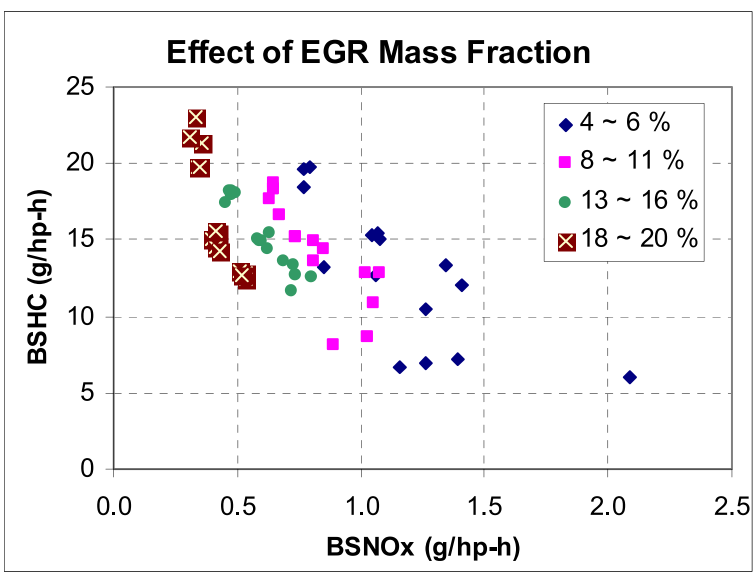


Figure 8: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 5

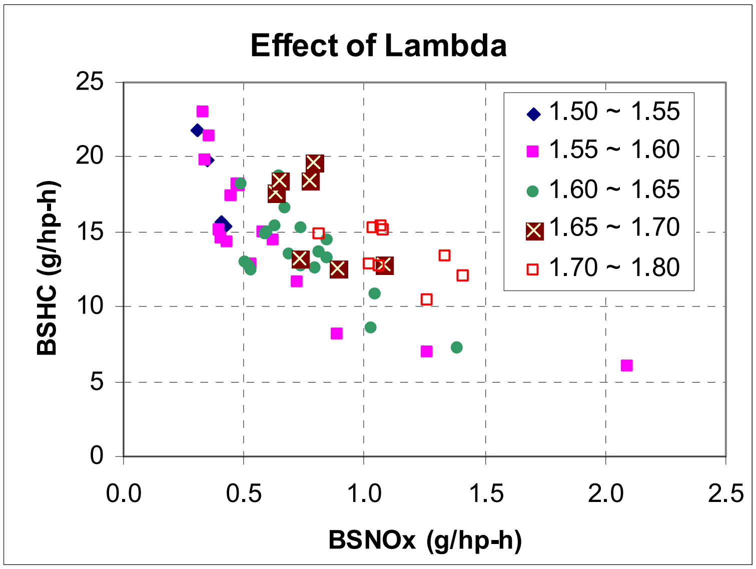


Figure 9: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 5

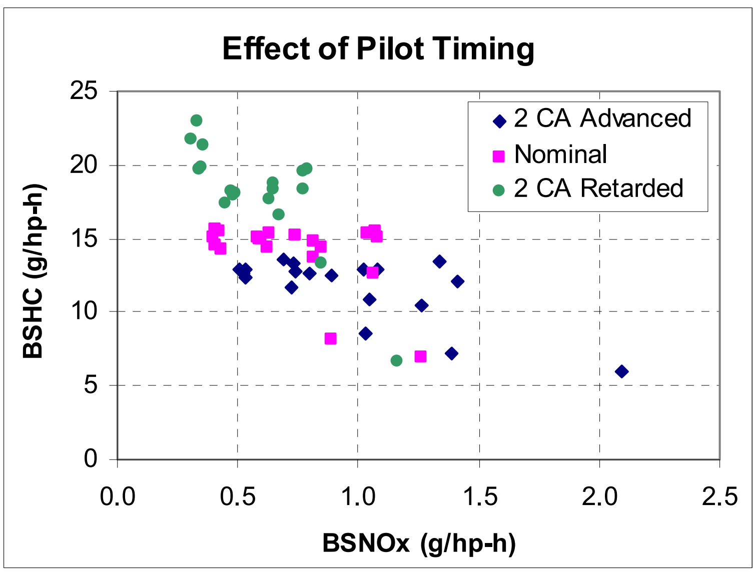


Figure 10: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 5

Figures 8-10 suggest that:

- NO_x is reduced 4% for 1% EGR mass fraction
- EGR and pilot injection timing are the dominant parameters in NO_x reduction
- HC increases drastically when pilot injection timing is retarded
- Wall quenching (quenching of the flame front close to the cylinder walls) becomes more pronounced at retarded pilot timing

6.2.4 ESC Mode 7 (1291 rpm, 25% load)

The parametric study was performed at 1291 rpm and 25% load. ACT was maintained at 26-31^{o}C. While EGR mass fraction was manually adjusted at 5%-20%, the TAB valve was modulated to vary the Corrected λ_{gas} at 1.5-1.9 and pilot injection timing was adjusted to +/- 2 degrees CA from the nominal timing. Figures 11-13 show the effects of EGR rate, Corrected λ_{gas}, and pilot timing on the HC and NO_x tradeoff. The HC tradeoff for NO_x appears to deteriorate compared with the tradeoff at 50% load.

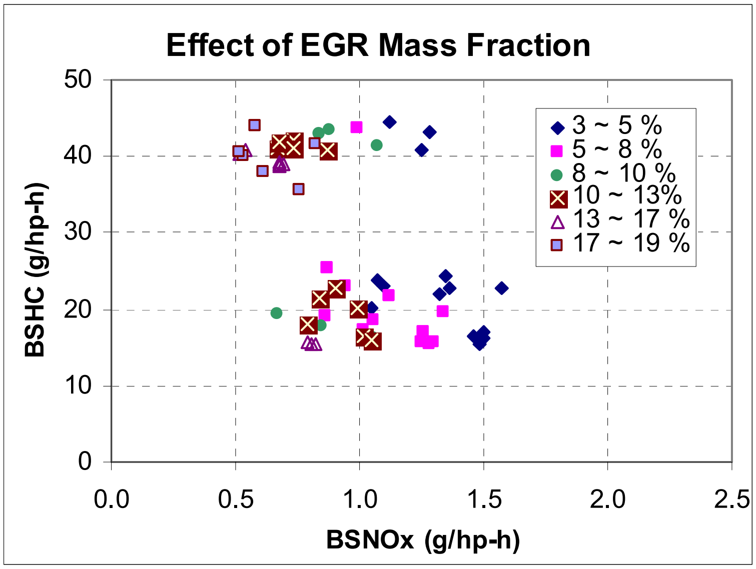


Figure 11: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 7

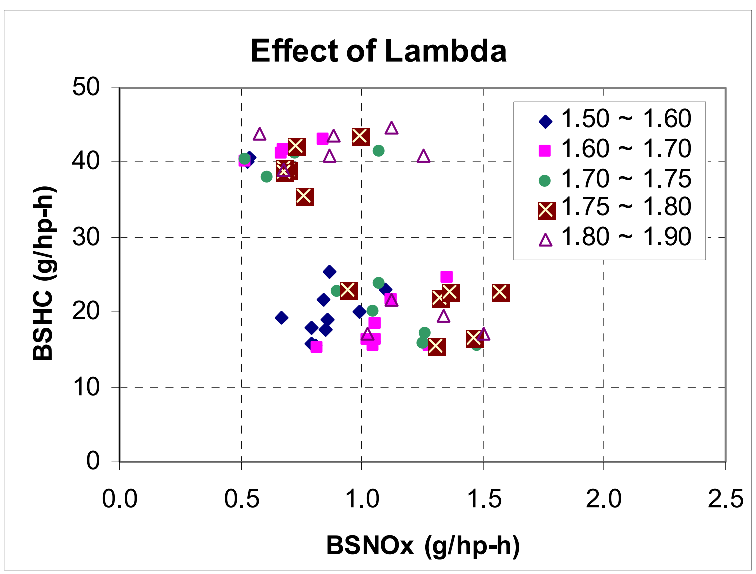


Figure 12: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 7

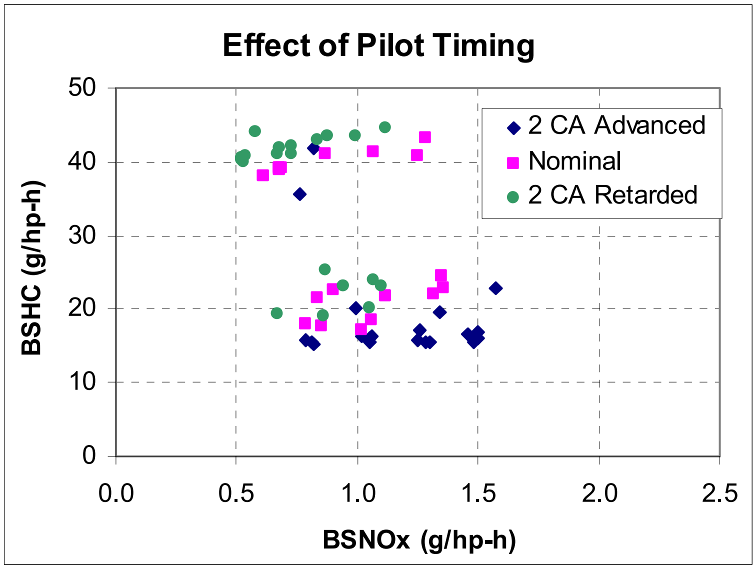


Figure 13: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 7

The Dual-Fuel engine was operated under "Skip-Fire" mode at Mode 7; only 4 or 5 out of 6 cylinders were firing. Figures 11-13 show that the number of firing cylinders was not optimized because HC emissions were as high as 40 g/hp-h when 5 cylinders were firing.

6.2.5 ESC Mode 8 (1561 rpm, 100% load)

The parametric study was performed at 1561 rpm and 100% load. ACT was maintained at 43-49^{o}C. While EGR mass fraction was manually adjusted at 5 %-20%, the TAB valve was modulated to vary the Corrected λ_{gas} at 1.4-1.7 and pilot injection timing was advanced 2 degrees CA from nominal timing. While attempting to retard pilot timing by 2 degrees CA, engine output was noticeably reduced; thus no data was recorded. Figures 14-16 show the effects of EGR rate, Corrected λ_{gas}, and pilot timing on the HC and NO_x tradeoff.

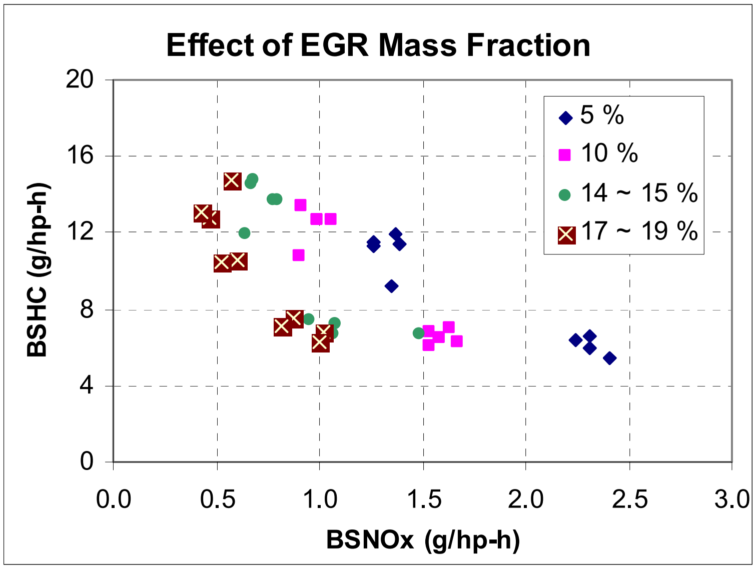


Figure 14: Effect of EGR on HC-NO$_x$ Tradeoff, ESC Mode 8

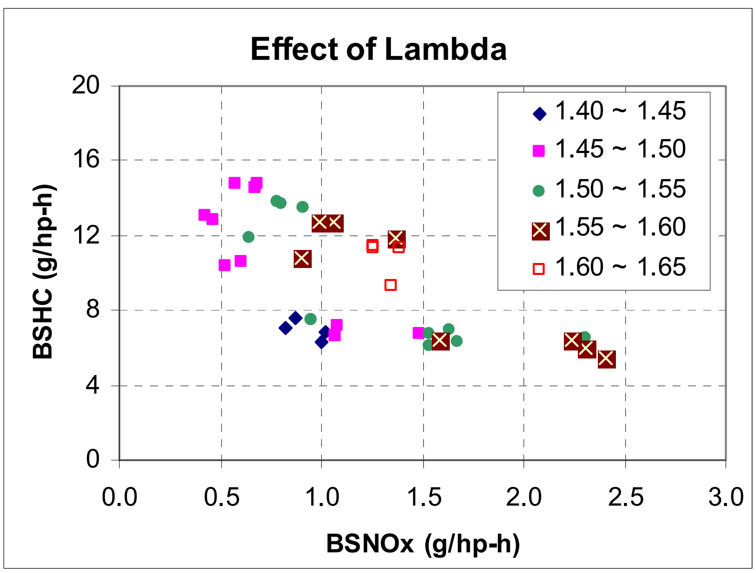


Figure 15: Effect of Corrected λ_{gas} on HC-NO$_x$ Tradeoff, ESC Mode 8

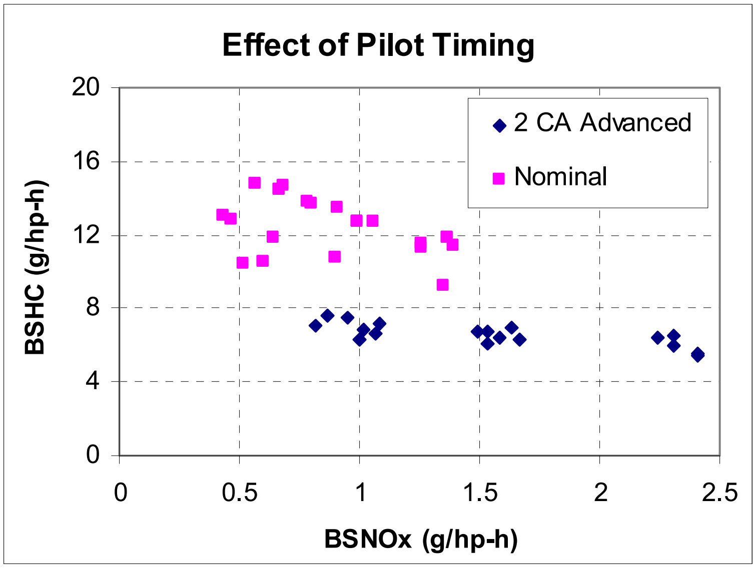


Figure 16: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 8

Figures 14-16 suggest that:

- NO_x is reduced 4% for 1% EGR mass fraction
- EGR and pilot injection timing are the dominant parameters in NO_x reduction
- There is an unfavorable HC tradeoff for NO_x when pilot injection timing is retarded

6.2.6 ESC Mode 4 (1561 rpm, 75% load)

The parametric study was performed at 1561 rpm and 75% load. ACT was maintained at 34-41°C. While EGR mass fraction was manually adjusted at 5%-20%, the TAB valve was modulated to vary the Corrected λ_{gas} at 1.5-1.8, and pilot injection timing was adjusted +/-2 degrees CA from nominal timing. Figures 17-19 show the effects of EGR rate, Corrected λ_{gas}, and pilot timing on the HC and NO_x tradeoff.

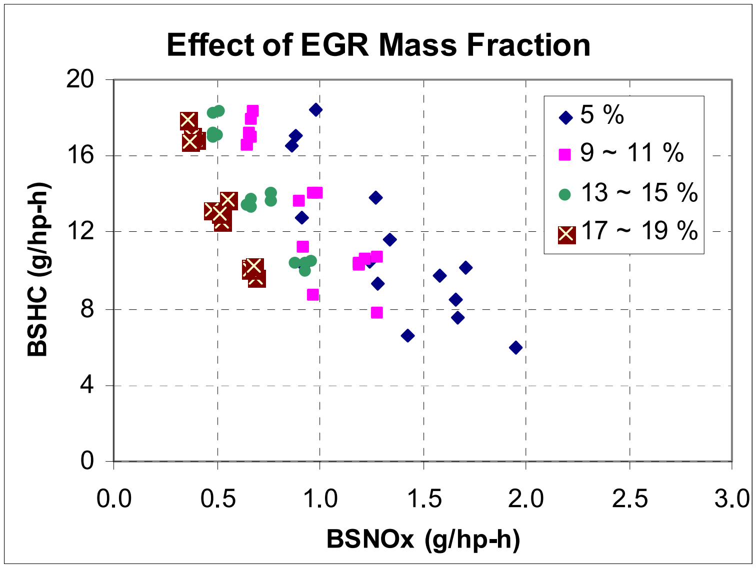


Figure 17: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 4

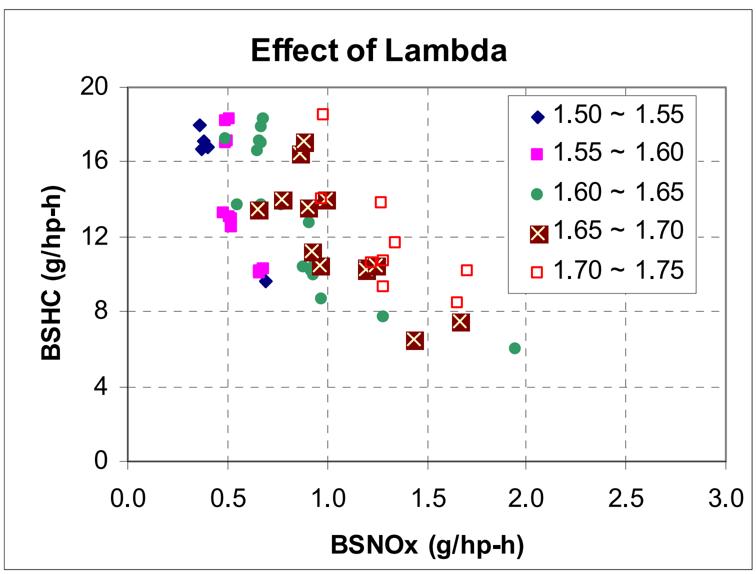


Figure 18: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 4

Figure 17 suggests that NO_x is reduced 4% with 1% EGR mass fraction. Although EGR and pilot injection timing are the dominant parameters affecting NO_x emissions, Figure 19 shows that an unfavorable HC-NO_x tradeoff is evident with retarded pilot injection timing. Wall quenching may become more pronounced at retarded ignition resulting from retarded pilot injection timing.

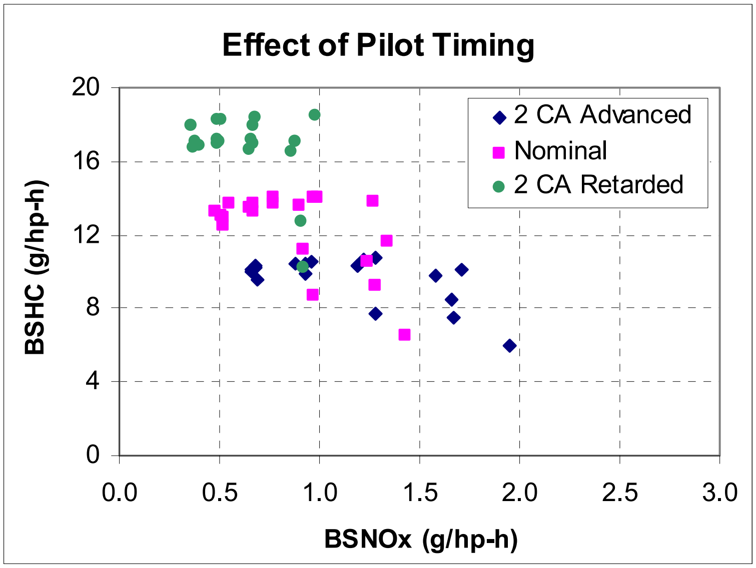


Figure 19: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 4

6.2.7 ESC Mode 3 (1561 rpm, 50% load)

The parametric study was performed at 1561 rpm and 50% load. ACT was maintained at 28-35°C. While EGR mass fraction was manually adjusted at 5%-20%, the TAB valve was modulated to vary the Corrected λ_{gas} at 1.6-1.9, and pilot injection timing was adjusted +/-2 degrees CA from nominal timing. Figures 20-22 show the effects of EGR rate, Corrected λ_{gas}, and pilot timing on the HC and NO_x tradeoff.

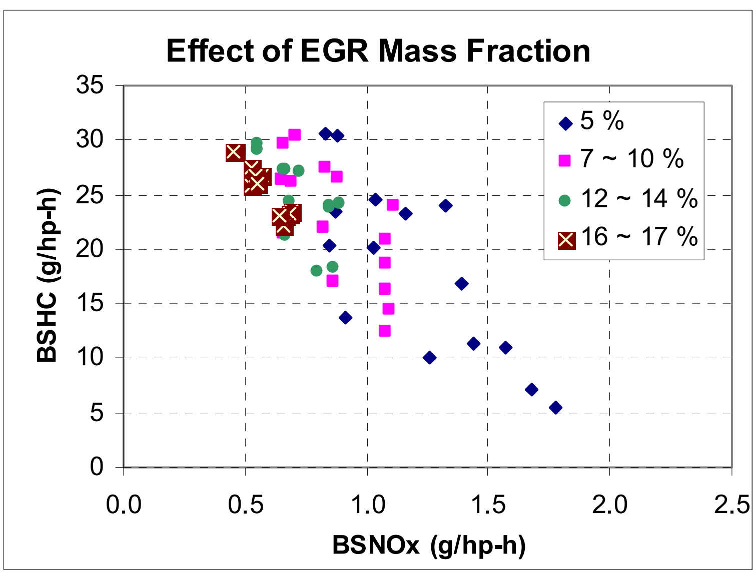


Figure 20: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 3

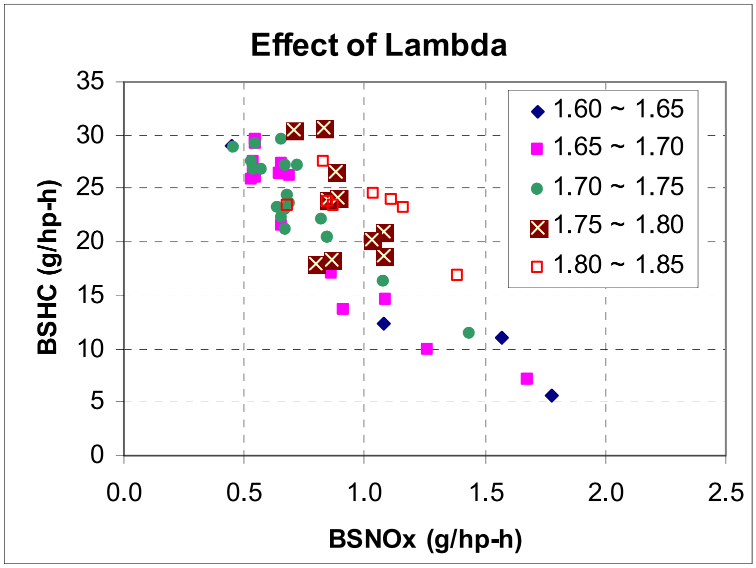


Figure 21: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 3

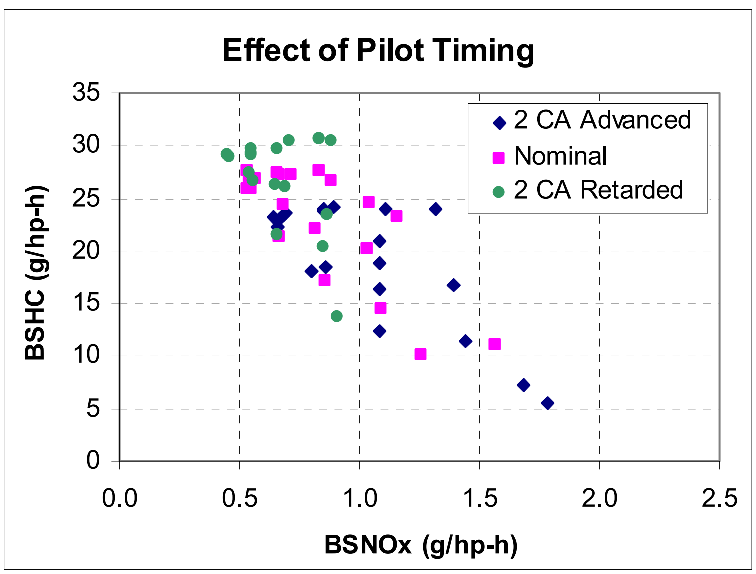


Figure 22: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 3

6.2.8 ESC Mode 9 (1561 rpm, 25% load)

The parametric study was performed at 1561 rpm and 25% load. ACT was maintained at 28-32^{o}C. While EGR mass fraction was manually adjusted at 5%-20%, the TAB valve was modulated to vary the Corrected λ_{gas} at 1.4-1.9, and pilot injection timing was adjusted to +/- 2 degrees CA from nominal timing. Figures 23-25 show the effects of EGR rate, Corrected λ_{gas}, and pilot timing on the HC and NO_x tradeoff. The HC tradeoff for NO_x appears to deteriorate compared with the tradeoff at 50% load.

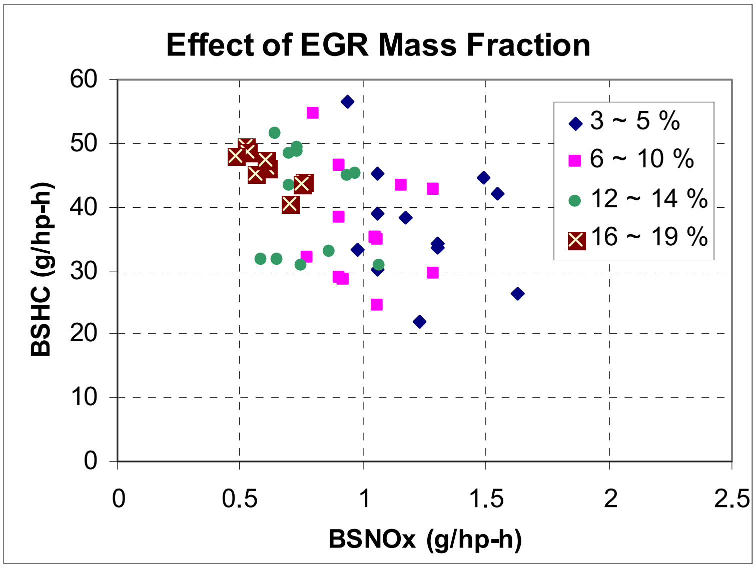


Figure 23: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 9

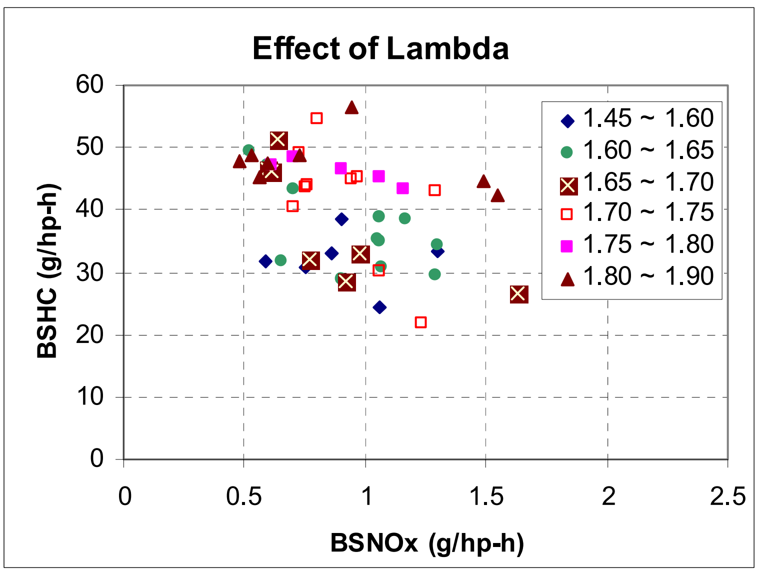


Figure 24: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 9

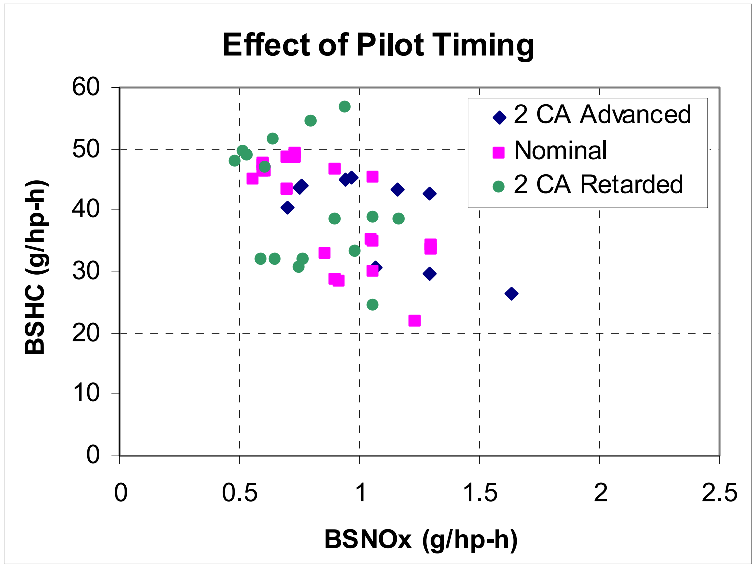


Figure 25: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 9

6.2.9 ESC Mode 10 (1830 rpm, 100% load)

The parametric study was performed at 1830 rpm and 100% load. ACT was maintained at 47-53^{o}C. While EGR mass fraction was manually adjusted at 5%-20%, the TAB valve was modulated to vary the Corrected λ_{gas} at 1.5-1.8, and pilot injection timing was adjusted to +/- 2 degrees CA from nominal timing. Figures 26-28 show the effects of EGR rate, Corrected λ_{gas}, and pilot timing on the HC and NO_x tradeoff.

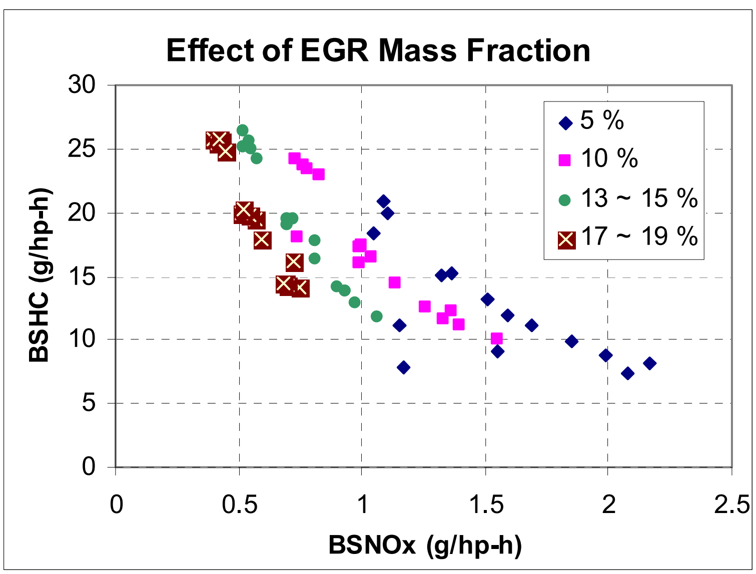


Figure 26: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 10

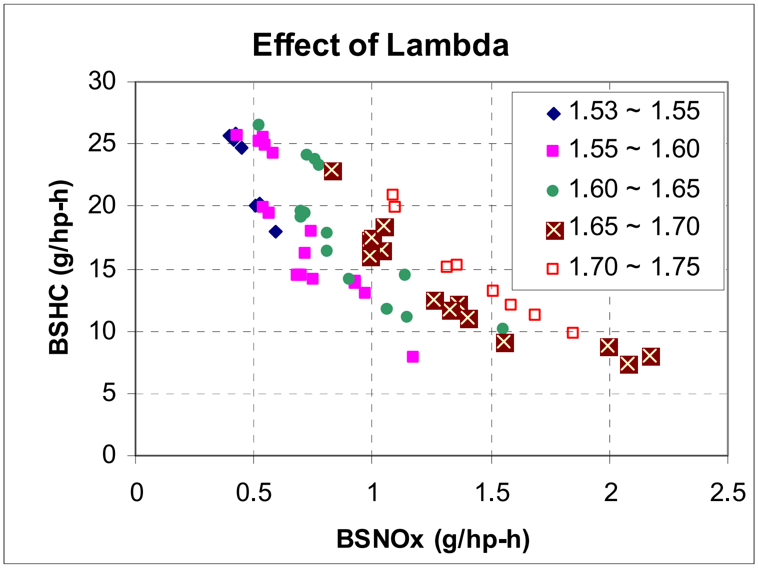


Figure 27: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 10

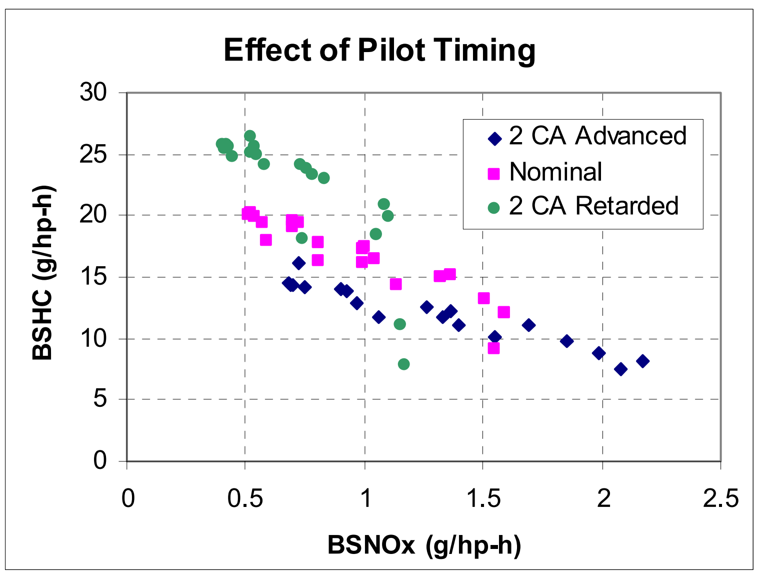


Figure 28: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 10

Figure 26 suggests that NO_x is reduced 4% with 1% EGR mass fraction. Although both EGR and pilot injection timing are the dominant parameters affecting NO_x emissions, Figure 28 shows an unfavorable HC-NO_x tradeoff with retarded pilot injection timing.

6.2.10 ESC Mode 12 (1830 rpm, 75% load)

The parametric study was performed at 1830 rpm and 75% load. ACT was maintained at 42-52°C. While EGR mass fraction was manually adjusted at 5%-20%, the TAB valve was modulated to vary the Corrected λ_{gas} at 1.5-1.8, and pilot injection timing was adjusted to +/- 2 degrees CA from nominal timing. Figures 29-31 show the effects of EGR rate, Corrected λ_{gas}, and pilot timing on the HC and NO_x tradeoff.

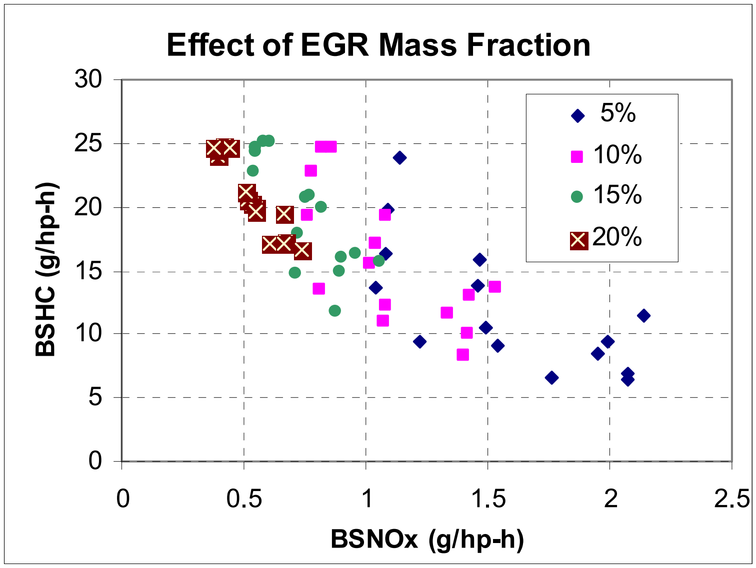


Figure 29: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 12

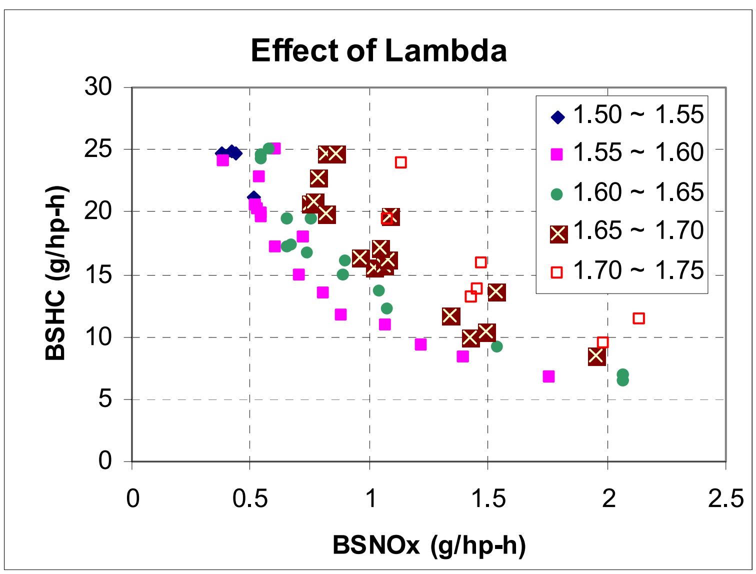


Figure 30: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 12

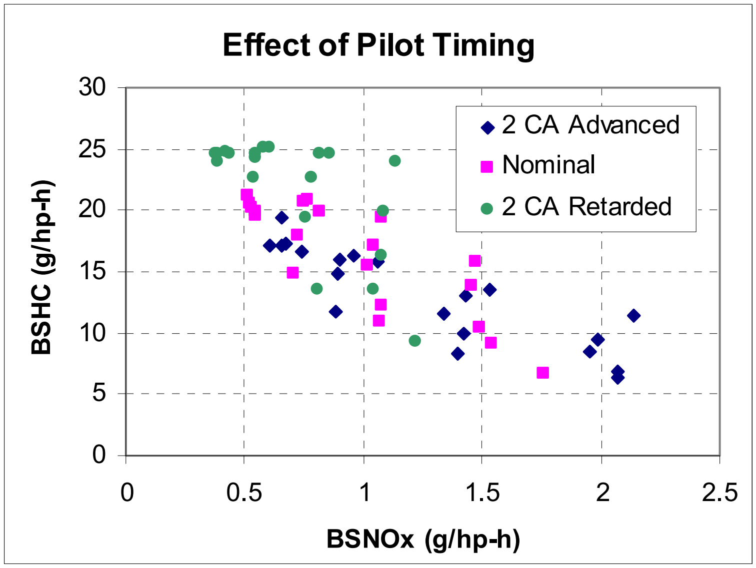


Figure 31: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 12

Figure 29 indicates a similar trend of an approximately 4% reduction in NO_x for 1% EGR mass fraction. Although both EGR and pilot injection timing are the dominant parameters affecting NO_x emissions, Figure 31 shows an unfavorable HC-NO_x tradeoff with retarded pilot injection timing.

6.2.11 ESC Mode 13 (1830 rpm, 50% load)

The parametric study was performed at 1830 rpm and 50% load. ACT was maintained at 32-39^{o}C. While EGR mass fraction was manually adjusted at 5%-20%, the TAB valve was modulated to vary the Corrected λ_{gas} at 1.4-1.9, and pilot injection timing was adjusted to +/- 2 degrees CA from nominal timing. Figures 32-34 show the effects of EGR rate, Corrected λ_{gas}, and pilot timing on the HC and NO_x tradeoff.

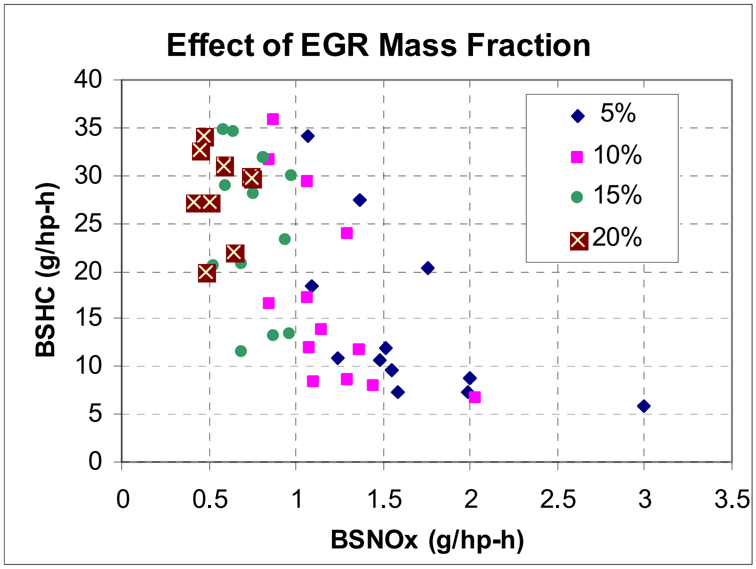


Figure 32: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 13

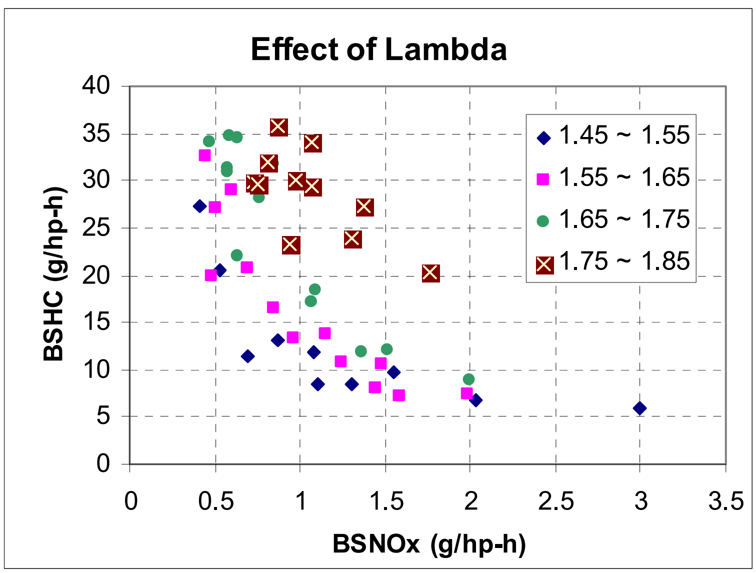


Figure 33: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 13

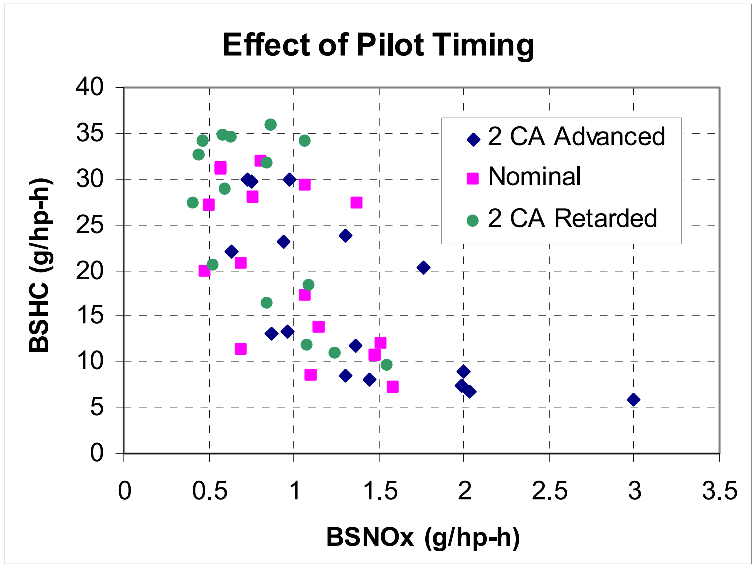


Figure 34: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 13

6.2.12 ESC Mode 11 (1830 rpm, 25% load)

The parametric study was performed at 1830 rpm and 25% load. ACT was maintained at 26-31°C. While EGR mass fraction was manually adjusted at 5%-20%, the TAB valve was modulated to vary the Corrected λ_{gas} at 1.3-1.9, and pilot injection timing was adjusted to +/- 2 degrees CA from nominal timing. Figures 35-37 show the effects of EGR rate, Corrected λ_{gas}, and pilot timing on the HC and NO_x tradeoff. The HC tradeoff for NO_x appears to deteriorate compared with the tradeoff at 50% load.

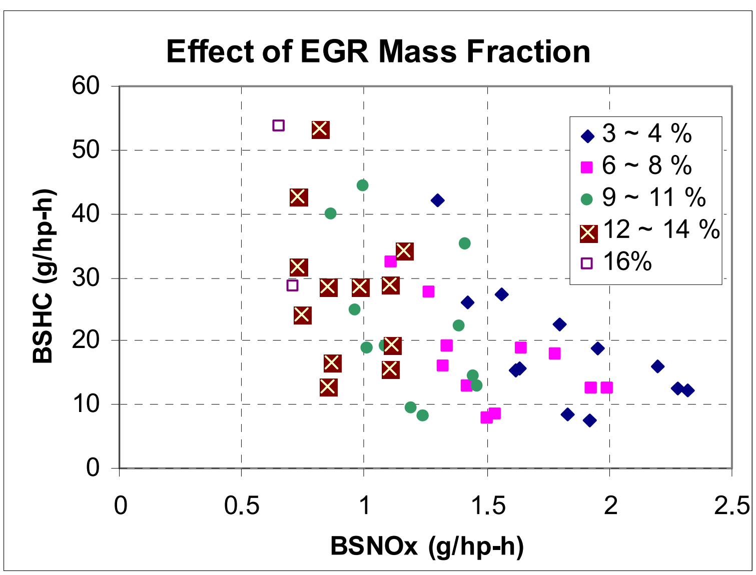


Figure 35: Effect of EGR on HC-NO_x Tradeoff, ESC Mode 11

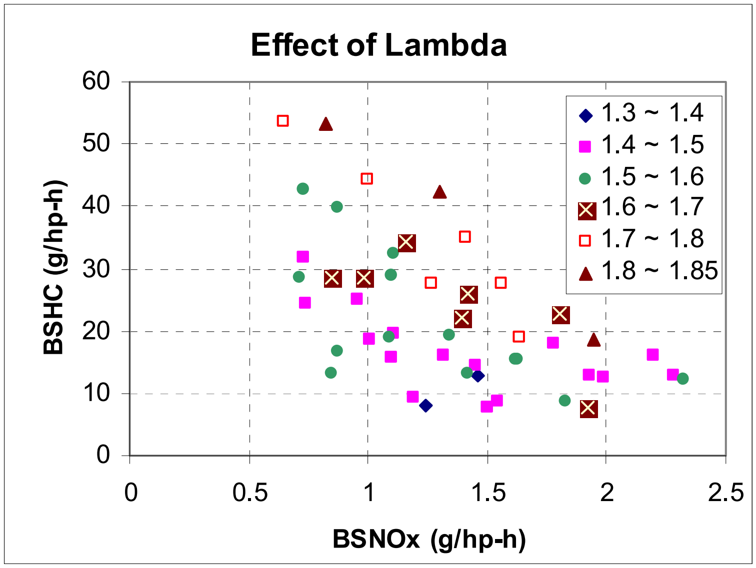


Figure 36: Effect of Corrected λ_{gas} on HC-NO_x Tradeoff, ESC Mode 11

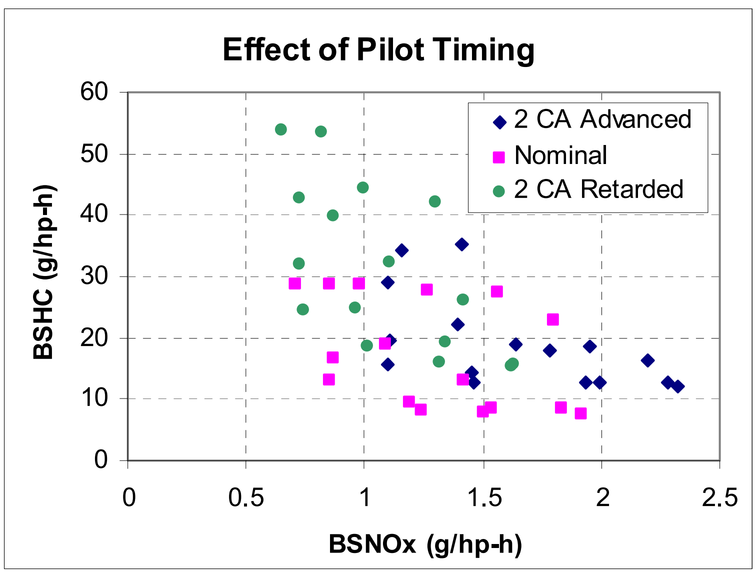


Figure 37: Effect of Pilot Timing on HC-NO_x Tradeoff, ESC Mode 11

6.3 Discussion

The PACCOLD-EGR system was evaluated and studied through parametric study, data reduction, and analysis. The NO_x and HC tradeoff and combustion characteristics were investigated at engine speeds of 1291, 1561, and 1830 rpm and engine loads of 25%, 50%, 75%, and 100%. These represent the ESC 13-mode cycle except low idle.

6.3.1 Exhaust Gas Recirculation

Displacing some of an engine's intake air with inert material is one NO_x reduction strategy. One method of intake air dilution is EGR, which effectively reduces NO_x emissions. During this process, part of the exhaust gas is reintroduced into the intake air and induced back into the engine.

The recirculated exhaust gases absorb a portion of the energy released during combustion of the fuel. This decreases the peak combustion temperature, which is the most critical parameter favoring high NO_x formation. This occurs primarily because the carbon dioxide (CO_2) content is significantly increased, and CO_2 has a much higher specific heat capacity than nitrogen (N_2). Another reason for lower peak combustion temperature is that recirculated exhaust gases do not participate in combustion as would fresh air. Furthermore, the EGR fraction displaces fresh oxygen, making less available for combustion and thus reducing the probability of interaction between nitrogen and oxygen atoms even under lean conditions. Figure 38 shows the effect of EGR mass fraction on NO_x emissions at ESC Mode 10 (1830 rpm and 100% load) at various Corrected λ_{gas} settings. Corrected λ_{gas} was adjusted from its desired value of 1.75-1.55 by modulating the TAB valve. It suggests a reduction in NO_x of about 4% for 1% EGR fraction as a working guideline.

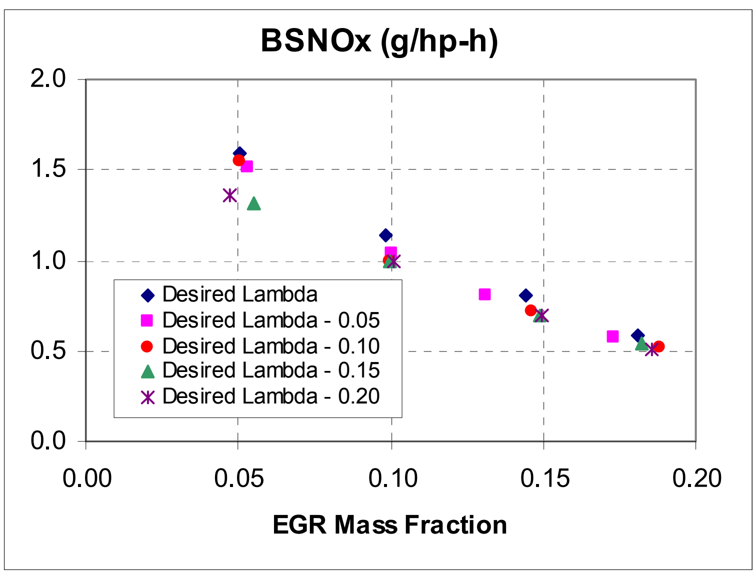


Figure 38: Effect of EGR Fraction on NO_x Emissions, ESC Mode 10

Other EGR effects are increased ignition delay and slower heat release rate, resulting in a retarded peak pressure location and thus reduced peak cylinder pressure levels. Figure 39 shows the effect of EGR mass fraction combined with Corrected λ_{gas} on start of combustion at ESC Mode 8 (1561 rpm and 100% load). Start of combustion is defined as the time to achieve 5% mass-burned fraction.

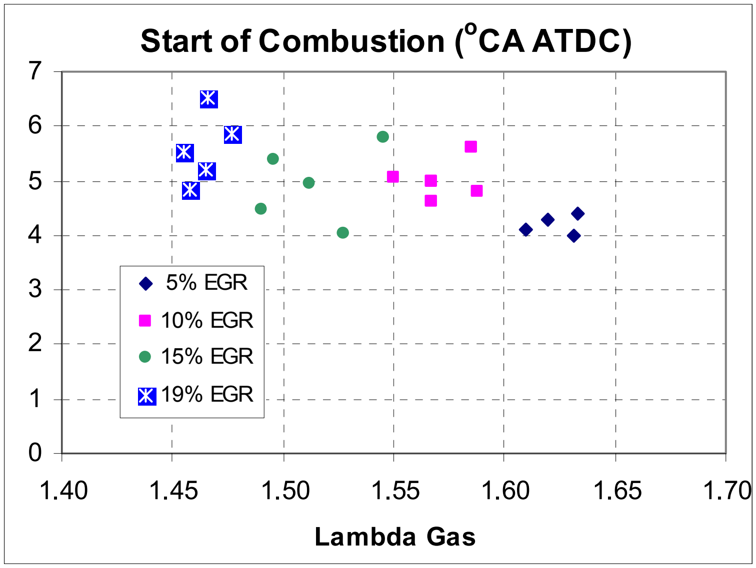


Figure 39: Effect of λ_{gas} and EGR on Start of Combustion, ESC Mode 8

6.3.2 PACCOLD-EGR

The EGR systems used in practice are mostly external systems, either high-pressure loop (HPL) or LPL systems.

The HPL EGR system requires either a venturi-type intake portion, including a throttled bypass to force exhaust gas into the intake system because the boost pressure is higher than the exhaust gas backpressure, or check valves to use the exhaust gas pressure pulsation in the exhaust manifold.

The LPL EGR system uses a particulate filter to protect the compressor wheel from particles. Rather than sourcing EGR from a pre-turbine location, the LPL EGR system uses exhaust gas that has been filtered. This configuration preserves turbocharger performance by allowing all the exhaust gas to be used in the turbine and requires less EGR cooling. Recirculated exhaust gas is introduced back upstream of the compressor; therefore, the LPL EGR system achieves the best mixture of exhaust gas and fresh air based on the efficient mixing process of the two gases inside the compressor. The PACCOLD-EGR system demonstrated in this project is a LPL system that uses a passive regenerating particulate filter.

6.3.3 Catalytic Particulate Filter

Performance and reliability of the particulate filter are crucial to the success of the PACCOLD-EGR. The Engelhard DPX catalytic soot filter was selected for this project. The DPX has been evaluated and demonstrated on trucks and buses for more than a year.

The DPX filter is a catalyzed ceramic wall-flow filter. It uses a dual function platinum catalyst combined with a base metal oxide catalyst. The catalyst coating is impregnated into the porous walls of the filter element. Figure 40 shows a schematic of a catalytic particulate filter (CPF). The function of the catalyst in the CPF is to lower the soot combustion temperature to facilitate regeneration of the filter by oxidation of PM under normal operating exhaust temperatures.

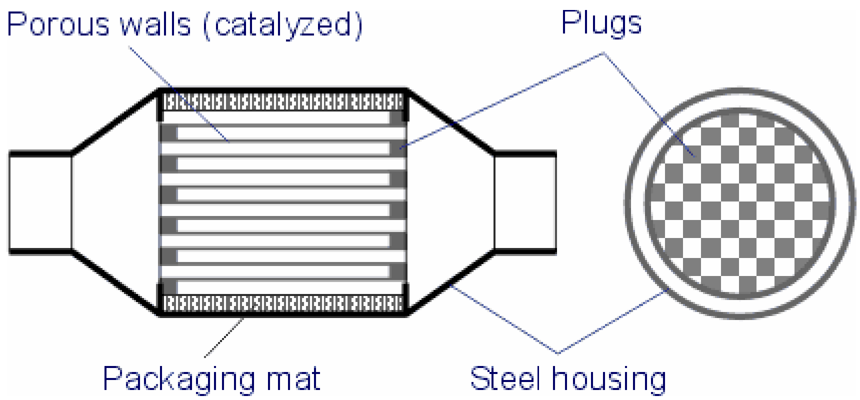


Figure 40: Schematic of Catalyzed Ceramic Particulate Filter (Courtesy of DieselNet Technology Guide)

Exhaust gas temperature and fuel-sulfur level are the important factors influencing the regeneration of the CPF. The rate of soot combustion increases with the filter temperature. Soot may accumulate in the filter if the temperature is too low, causing excessive flow restriction, high exhaust backpressure, and, eventually, clogging of the filter. The exhaust temperatures experienced during the regular operation of the Dual-Fuel engine are usually higher than those seen in diesel engines. This is due to the full-time lambda control strategy used in the Dual-Fuel engine. Unlike in diesel engines, excess air introduced to the Dual-Fuel engine is always controlled to its optimum values. Sulfur content of diesel fuel will not be an issue in the Dual-Fuel engine, which is predominantly fueled by natural gas. The California Air Resources Board (CARB) has verified CAP's CPF, allowing use of diesel with sulfur content no higher than diesel commercially available in California (typically 120 ppm sulfur). CAP's Dual-Fuel engines generally use 10% diesel as pilot fuel; therefore, the CPF is actually receiving fuel with sulfur content equivalent to 1.2 ppm.

6.4 PACCOLD-EGR Demonstration

The performance of a model year 2002 C-12 Dual-Fuel engine equipped with the PACCOLD-EGR system was demonstrated using the optimized calibrations for EGR rate, lambda, and pilot timing for the best NO_x and HC emissions tradeoff. Instead of the Federal Test Procedure (FTP), the 13-mode ESC was used to show a prediction for FTP performance. The dynamometer operation on the C-12 Dual-Fuel test engine shown in Table 2 was followed. Table 3 shows emissions and fuel consumption over the ESC test cycle, along with baseline results for comparison.

Table 3: PACCOLD-EGR Performance

	PACCOLD-EGR	Baseline	Change
THC, g/hp-h	17.7	12.38	+43%
NMHC, g/hp-h	1.44		
CO, g/hp-h	0.05	4.05	-98.8%
NO_x, g/hp-h	0.54	2.38	-77.3%
PM, g/hp-h	0.0037		
BSEC, Btu/hp-h	7,610	7,124	+6.8%
Gas Substitution, %	81.23	79.97	+1.6%

The performance results show a 6.8% BSEC increase, which is due to the unburned hydrocarbon emissions. Most of the unburned HC emissions are methane. The possible sources of HC emissions include in-cylinder crevices, quenching of the flame front close to the cylinder walls, and bulk quenching of the mixture of fuel, air, and recirculated exhaust gases in partially misfiring engine cycles. Most likely, wall quenching is the dominant source of unburned HC in the C-12 Dual-Fuel engine equipped PACCOLD-EGR owing to the increased ignition delay and much higher specific heat capacity of the recirculated gas. In part load (or low brake mean effective pressure), the wall quenching effect is more pronounced because the combustion temperature is relatively low. It is expected that fuel efficiency will be improved by reducing the desired lambda (i.e., using a richer mixture) at part load conditions. Appendix 2 details the ESC 13-mode test results with PACCOLD-EGR.

6.5 ACCOLD-EGR

The ACCOLD-EGR system, which includes the LNC as shown in Figure 2, was not pursued in this project after careful consideration of the following:

1. Tests performed by the Diesel Emissions Control–Sulfur Effects (DECSE) Program guided by DOE, NREL, Oak Ridge National Laboratory, the Engine Manufacturers Association, and the Manufacturers of Emission Controls Association have shown:
    - NO_x reduction efficiency below 20% with 4% fuel penalty
    - 50% and 30% NO_x reduction observed at specific operating temperatures for low-temperature and high-temperature catalysts, respectively
2. Compared with urea-based selective catalytic reduction (urea-SCR), which achieves better than 80% NO_x reduction, the LNC (HC-SCR) is not an attractive method for NO_x reduction.
3. The U.S. Environmental Protection Agency (EPA) believes that NO_x absorber catalyst technology will be successfully implemented on heavy-duty diesel engines in 2007-2010 for NO_x reduction, although it is a less mature technology compared with CPFs.

4. Industry in Europe favors urea-SCR systems for meeting Euro V NO_x emission requirements.
5. The Advanced Petroleum-Based Fuels–Diesel Emissions Control (APBF-DEC) program, the successor to the DECSE Program, has been focusing on two integrated systems in 2000-2004: NO_x absorber and DPF and urea-SCR and DPF.
6. There is lack of support from the government and private sectors; development of LNC technology is suspended indefinitely.

In December 2002, CAP notified NREL that there would be no significant technical merit in proceeding with the ACCOLD-EGR system as proposed. Without support from the government and the exhaust emissions control industry for further development of LNC technology, commercial viability and implementation of ACCOLD-EGR is very uncertain. It was determined in January 2003, in the interests of all parties concerned, that CAP should not pursue the development and analysis of the ACCOLD-EGR system proposed for this project.

7.0 Application and Feasibility of PACCOLD-EGR

The PACCOLD-EGR system has demonstrated technical viability, achieving 0.5 g/hp-h NO_x and 0.004 g/hp-h PM emissions on the C-12 Dual-Fuel engine. This section discusses the commercial implementation of the technology into the heavy-duty on-highway NGV market.

The PACCOLD-EGR system consists of the following major components:

- CPF
- Venturi
- EGR cooler
- EGR valve

Successful implementation of PACCOLD-EGR technology will rely on the development of these components.

7.1 Catalytic Particulate Filter

Control technologies for PM have seen significant progress in recent years. Commercial application of the Engelhard DPX and Johnson-Matthey CRT (continuously regenerating technology) filters began in 2002.

In August 2002, CARB verified CAP's CPF, manufactured by Engelhard, for use with a specified list of natural gas/diesel Dual-Fuel engines. This verification applies to specific CAP engines and to Caterpillar engines that have been converted to Dual-Fuel operation using CAP Dual-Fuel retrofit systems.

Under normal operating conditions, the DPX and CRT filter systems are expected to operate successfully for many years. Periodic maintenance is required for both systems to remove the accumulated engine lube oil ash, which is collected within the wall-flow filter because it is not combustible. Further improvements to CPFs have continued, including better soot regeneration characteristics, better methods for dealing with oil ash, and reduced exhaust backpressure while maintaining a high level of PM control. All of the diesel engine manufacturers plan to apply this technology fleet-wide by 2007.

Exhaust temperatures experienced during regular operation of the Dual-Fuel engine are usually higher than those experienced in diesel engines. Unlike in diesel engines, excess air introduced to the Dual-Fuel engine is always controlled to its optimum values. In addition to higher exhaust temperature, Dual-Fuel engines produce less soot than diesel engines. Therefore, the performance requirements on soot regenerating characteristics for Dual-Fuel engines are less demanding. Because the Dual-Fuel engine is predominantly fueled by natural gas, diesel sulfur content below 15 ppm will not be required. Diesel with a sulfur content no higher than that in commercially available California diesel is acceptable.

7.2 EGR Components

EGR systems have proven to be effective tools for helping passenger car and light-duty applications meet emission requirements. EGR is a viable technology and an important contributor to meeting the 2004 EPA NO_x emission standards for heavy-duty on-highway diesel truck engines.

An EGR system invariably includes one or more control valves and an EGR cooler. The remainder of the EGR control system consists of piping, flanges, and gaskets. Exhaust constituents may cause erosion and/or corrosion in the EGR system components; therefore, the challenge is to select, design, and develop reliable and trouble-free EGR systems. The following issues must be addressed:

- Material buildup
- Contaminants
- Engine durability
- EGR cooler design
- EGR valve and control
- Piping

The level of challenge for PACCOLD-EGR would not be as high as that for the HPL EGR system with a CPF. With the October 2002 on-highway “pull-ahead” diesel emission standards deadline, development of EGR technologies has progressed rapidly. With considerable support from various industries and suppliers, EGR technologies have been implemented on most heavy-duty on-highway truck diesel engines starting October 2002. Therefore, CAP can select PACCOLD-EGR system components from those that already have been validated and tested on-road.

8.0 Summary and Conclusions

The PACCOLD-EGR technology was investigated, assessed, and demonstrated during this project under the NREL contract. The project resulted in the following conclusions:

1. The C-12 Dual-Fuel engine equipped with the PACCOLD-EGR system demonstrated 0.5 g/hp-h NO_x and 0.004 g/hp-h PM.

2. The PACCOLD-EGR system is a viable technology, and commercial implementation of this technology is based on fully validated components available today.
3. A reduction in NO_x of about 4% for 1% of EGR mass fraction is suggested as a working guideline.
4. EGR mass fraction and pilot injection timing are the dominant parameters affecting NO_x emissions.
5. Unfavorable HC tradeoff for NO_x is evident with retarded pilot injection timing.
6. A THC catalyst will be required to further reduce NMHC and methane emissions.

9.0 References

1. LeTavec C. et al., "Year-Long Evaluation of Trucks and Buses Equipped with Passive Diesel Particulate Filters," SAE Paper 2002-01-0433.
2. Majewski A., "Catalyzed Diesel Filter," Technology Guide, Revision 2002.03.
3. Andersson S. et al., "Low Pressure EGR Calibration Strategies for Reliable Diesel Particulate Filter Regeneration on HDD Engines," SAE Paper 2002-01-2780.
4. Bradley R., "Technology Roadmap for the 21st Century Truck Program," December 2000.
5. Diesel Emission Control-Sulfur Effects (DECSE) Program, "Final Report: Diesel Oxidation Catalysts and Lean-NO_x Catalysts," June 2001.
6. U.S. Department of Energy, "Multiyear Program Plan, Advanced Petroleum-Based Fuels (APBF) RD&T for Compression-Ignition, Direct-Injection Engines and Emission Control Systems," November 2000.
7. Künkel C., "Catalytic Reduction of NO_x on Heavy-Duty Trucks," Doctoral Thesis, September 2001.
8. U.S. Environmental Protection Agency, "Highway Diesel Progress Review," June 2002, EPA420-R-02-016.
9. California Air Resources Board, "2002-08-15 Clean Air Partners Verification Letter."

Appendix 1
Model Year 2002 C-12 Dual-Fuel Engine Baseline ESC 13-Mode Test Results

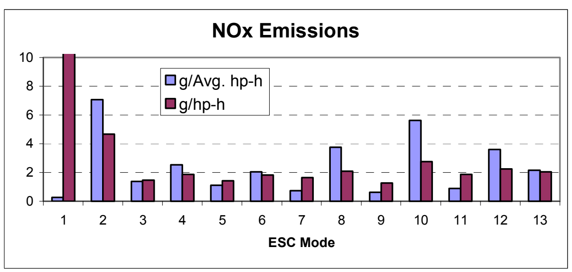
ENGINE: 2002MY C12
410 hp @ 1800 rpm, 1250 ft-lb @ 1200 rpm

TEST DATE: 04/12/02
BIN FILE: C120009

DAQ FILE: 2001
Flash File: 2071582-01

	Test No.	2001-1	2001-2	2001-3	2001-4	2001-5	2001-6	2001-7	2001-8	2001-9	2001-10	2001-11	2001-12	2001-13	Weighted
	Test Mode	1	2	3	4	5	6	7	8	9	10	11	12	13	Average
INPUTS:	UNITS														
Hydrocarbon Concentration	PPM	125	68	9113	5316	7342	3753	7747	4470	10437	3749	10885	5146	5833	
Carbon Monoxide Concentration	PPM	95	29	1501	790	1186	520	1884	627	1722	558	1665	810	1098	
Nitrogen Oxides Concentration	PPM	135	705	182	275	185	281	155	317	104	436	132	330	278	
Manifold Air Flow	SCFM	125.4	597.9	453.3	548.4	357.3	431.6	290.4	708.0	369.9	768.3	410.5	651.7	462.1	
	g/min	4,226	20,147	15,276	18,480	12,040	14,543	9,787	23,857	12,464	25,892	13,834	21,959	15,571	
Diesel Delivery	g/min	23.4	793.8	66.6	66.6	51.0	51.6	41.4	66.0	53.4	84.0	74.4	88.2	91.8	118.3
CNG Delivery	g/min	0.0	0.0	486.0	624.6	392.4	510.6	270.0	802.2	314.4	889.8	331.8	723.0	494.4	422.0
BSFC	BTU/HPc-hr	23,085	6,252	7,821	6,810	7,629	6,674	9,118	6,379	9,747	6,343	11,022	6,707	7,367	
CNG Percentage	%	0.0	0.0	89.1	91.3	89.6	91.7	87.9	93.2	86.8	92.2	83.3	90.2	85.8	
Engine Speed	RPM	701	1292	1563	1564	1293	1293	1293	1564	1564	1833	1833	1833	1833	
Observed Torque	ft.-lb.	18.4	1235.1	631.5	907.2	628.2	913.6	369.5	1209.0	336.8	1163.2	278.2	917.7	603.6	
	Nm	24.9	1674.6	856.2	1229.9	851.7	1238.6	501.0	1639.2	456.7	1577.1	377.1	1244.2	818.3	
Weighting Factor	%	15	8	10	10	5	5	5	9	10	8	5	5	5	
OUTPUTS:	UNITS														
Manifold Air Flow	LBm/min	9.39	44.78	33.95	41.08	26.76	32.32	21.75	53.03	27.70	57.55	30.75	48.81	34.61	
Diesel Delivery	LBm/min	0.05	1.75	0.15	0.15	0.11	0.11	0.09	0.15	0.12	0.19	0.16	0.19	0.20	
CNG Delivery	LBm/min	0.00	0.00	1.07	1.38	0.87	1.13	0.60	1.77	0.69	1.96	0.73	1.59	1.09	
Exhaust Mass Flow	LBm/min	9.45	46.53	35.17	42.60	27.74	33.56	22.44	54.94	28.51	59.69	31.64	50.60	35.90	
Hydrocarbon Mass Emissions	g/hr.	15.40	40.99	4166.64	2944.14	2647.65	1637.37	2259.92	3192.34	3868.82	2909.58	4477.50	3384.53	2722.59	2480.104
Carbon Monoxide Mass Emissions	g/hr.	23.71	35.76	1388.80	884.78	865.06	459.36	1111.70	905.69	1291.29	875.54	1385.67	1077.60	1037.20	811.29
Nitrogen Oxides Mass Emissions	g/hr.	55.10	1416.89	276.30	505.21	221.94	407.88	150.66	752.19	128.63	1123.77	180.79	721.20	431.64	475.93
Observed Brake Horsepower	BHP	2.5	303.9	188.0	270.1	154.6	224.9	91.0	360.0	100.3	405.9	97.1	320.2	210.6	200.30
HC Emissions	g/avg. hp-h	0.08	0.20	20.80	14.70	13.22	8.17	11.28	15.94	19.32	14.53	22.35	16.90	13.59	
CO Emissions	g/avg. hp-h	0.12	0.18	6.93	4.42	4.32	2.29	5.55	4.52	6.45	4.37	6.92	5.38	5.18	
NOx Emissions	g/avg. hp-h	0.28	7.07	1.38	2.52	1.11	2.04	0.75	3.76	0.64	5.61	0.90	3.60	2.15	
Specific NOx Emissions	g/hp-h	22.48	4.66	1.47	1.87	1.44	1.81	1.66	2.09	1.28	2.77	1.86	2.25	2.05	

Remarks:



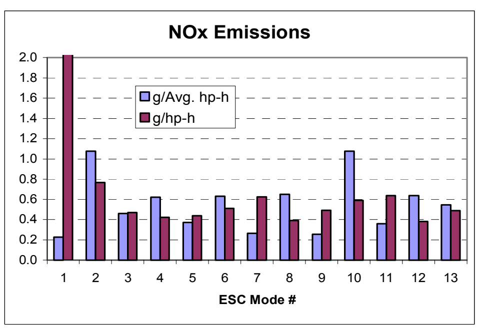
BSHC	**12.38 g/hp-h**
	16.60 g/kWh
BSCO	**4.05 g/hp-h**
	5.43 g/kWh
BSNOx	**2.38 g/hp-h**
	3.19 g/kWh
BSFC	**7124 Btu/hp-h**
Subsititution	**79.97 %**

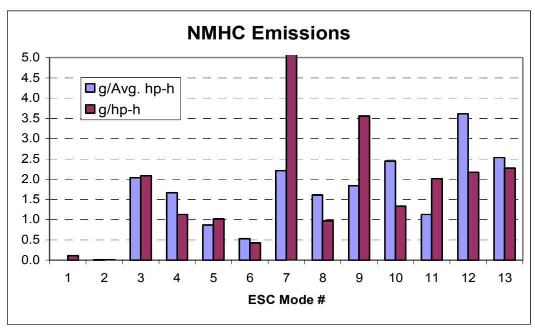
Appendix 2
Model Year 2002 C-12 Dual-Fuel Engine Equipped with PACCOLD-EGR ESC 13-Mode Test Results

ENGINE: 2002MY C12 | **TEST DATE:** 07/26/02 | **DAQ FILE:** 1081

410 hp @ 1800 rpm, 1250 ft-lb @ 1200 rpm | **BIN FILE:** C12EGR3 | **Flash File:** 2071582-01

	Test No.	1081-1	1081-2	1081-3	1081-4	1081-5	1081-6	1081-7	1081-8	1081-9	1081-10	1081-11	1081-12	1081-13	Weighted
	Test Mode	1	2	3	4	5	6	7	8	9	10	11	12	13	Average
INPUTS:	UNITS														
THC Concentration	PPM	12	13	11802	7689	7167	3429	18573	7223	12699	9063	6760	13010	13683	
Methane Concentration	PPM	9	10	10877	7091	6624	3171	16994	6672	11610	8335	6122	11940	12514	
CO Concentration	PPM	1	5	13	13	5	4	5	13	8	18	8	22	21	
NOx Concentration	PPM	101	144	63	67	71	93	57	67	46	97	61	57	76	
Manifold Air Flow	SCFM	126.0	402.3	374.5	476.6	290.4	355.6	234.7	533.5	286.9	589.0	346.3	564.8	466.0	
	g/min	4,245	13,558	13,388	16,860	9,679	12,336	8,594	17,746	10,369	20,372	10,880	20,470	13,133	
Diesel Delivery	g/min	27.0	703.2	64.2	62.4	52.2	52.2	33.0	57.0	39.0	81.6	61.8	81.6	95.4	107.3
CNG Delivery	g/min	0.0	0.0	490.8	681.6	378.6	523.2	226.8	754.2	290.0	804.0	288.0	816.6	503.4	415.3
BSFC	BTU/HPc-hr	20,717	6,613	8,337	7,472	7,428	6,892	9,020	7,187	9,354	7,141	9,076	7,968	7,866	
CNG Percentage	%	0.0	0.0	89.5	92.4	89.0	91.8	88.5	93.7	89.3	91.7	83.9	91.8	85.5	
Engine Speed	RPM	701	1294	1553	1559	1293	1293	1297	1564	1563	1835	1839	1824	1831	
Observed Torque	ft.-lb.	23.5	1032.3	601.0	899.9	629.0	908.6	311.3	1017.7	315.4	951.0	292.0	870.0	580.8	
	Nm	31.9	1399.6	814.8	1220.1	852.8	1231.9	422.1	1379.8	427.6	1289.4	395.9	1179.6	787.5	
Weighting Factor	%	15	8	10	10	5	5	5	9	10	8	5	5	5	
OUTPUTS:	UNITS														
Exhaust Mass Flow	kg/min	4.27	14.26	13.94	17.60	10.11	12.91	8.85	18.56	10.70	21.26	11.23	21.37	13.73	13.28716
THC Mass Emissions	g/hr	1.48	5.21	4722.70	3884.53	2079.41	1270.61	4719.68	3846.86	3899.15	5529.40	2178.78	7978.68	5392.50	3220.828
NMHC Mass Emissions	g/hr	0.35	1.32	370.09	302.14	157.53	95.40	401.27	293.47	334.45	444.00	205.69	656.33	460.53	261.5957
CO Mass Emissions	g/hr.	0.22	4.08	10.48	13.27	2.90	2.70	2.52	14.00	4.70	22.62	4.94	27.71	16.72	9.15
NOx Mass Emissions	g/hr.	41.10	195.23	83.76	112.79	67.86	114.42	48.13	118.42	46.34	195.84	65.07	116.03	98.95	97.92
Observed Brake Horsepower	BHP	3.14	254.34	177.71	267.12	154.85	223.63	76.89	303.00	93.86	332.26	102.24	302.14	202.48	181.65
NMHC Emissions	g/avg. hp-h	0.00	0.01	2.04	1.66	0.87	0.53	2.21	1.62	1.84	2.44	1.13	3.61	2.54	
CO Emissions	g/avg. hp-h	0.00	0.02	0.06	0.07	0.02	0.01	0.01	0.08	0.03	0.12	0.03	0.15	0.09	
NOx Emissions	g/avg. hp-h	0.23	1.07	0.46	0.62	0.37	0.63	0.26	0.65	0.26	1.08	0.36	0.64	0.54	
Specific NMHC Emissions	g/hp-h	0.11	0.01	2.08	1.13	1.02	0.43	5.22	0.97	3.56	1.34	2.01	2.17	2.27	
Specific NOx Emissions	g/hp-h	13.10	0.77	0.47	0.42	0.44	0.51	0.63	0.39	0.49	0.59	0.64	0.38	0.49	





NMHC	**1.44 g/hp-h** **1.93 g/kWh**
CO	**0.05 g/hp-h** **0.07 g/kWh**
NOx	**0.54 g/hp-h** **0.72 g/kWh**
PM	**0.0037 g/hp-h** **0.0050 g/kWh**
BSFC	**7610 Btu/hp-h**
Subsititution	**81.23 %**

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
July 2003

3. REPORT TYPE AND DATES COVERED
Subcontract Report

4. TITLE AND SUBTITLE
Next Generation Natural Gas Vehicle Program Phase I: Clean Air Partners 0.5 g/hp-h NOx Engine Concept; Final Report

5. FUNDING NUMBERS
FC03.1010
NDX-1-31070-01

6. AUTHOR(S)
H.C. Wong

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Clean Air Partners
San Diego, CA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/ SR-540-33957

11. SUPPLEMENTARY NOTES
NREL Technical Monitor: M. Frailey

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Subcontractor report details work done by Clean Air Partners to develop 0.5 g/hp-h NOx natural gas engine exhaust gas recirculation (EGR) technology for the Next Generation Natural Gas Vehicle Program.

14. SUBJECT TERMS
clean air partners; exhaust gas recirculation; egr; nox; ngngv; accold; paccold; natural gas; lng; dual-fuel

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL